Commonwealth of Massachusetts
Executive Office of Environmental Affairs
Department of Environmental Protection

Daniel S. Greenbaum
Commissioner

April 19, 1991

Dear Reader:

These *Standard References for Monitoring Wells*, WSC-310-91, describe the technical requirements for locating, drilling, installing, sampling and decommissioning monitoring wells. *Standard References for Monitoring Wells* was developed to help ensure data used for environmental monitoring purposes is valid and can be interpreted consistently by anyone assessing groundwater, including Department staff, consultants, drillers and firms performing these assessments.

Many people, from within and outside the Department, were involved in developing this technical document. These References represent the Department's current understanding of the art of groundwater monitoring. We welcome any information on innovative field techniques, suggestions for updates, or comments. This document will be updated to reflect new information about emerging technologies as our resources permit.

These References are one of several initiatives the Department is undertaking to provide clear, practical guidance for those affected by Massachusetts environmental regulations. We hope that you find this document a valuable tool.

Very truly Yours,

Daniel S. Greenbaum
Commissioner

COMMONWEALTH OF MASSACHUSETTS
DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS
WSC–310-91

DEDICATION

This document is dedicated with great affection to Dodie Brownlee. She pioneered hydrogeology in the Department of Environmental Protection. Dodie worked tirelessly to protect and improve our environment.

Dodie Brownlee conceived and developed these ***Standard References for Monitoring Wells****. She worked on them until her death in the spring of 1990.*

May her spirit of commitment and drive for excellence live on through all of us.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

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SECTION 1.1 FOREWORD

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SECTION 1.1 FOREWORD

1.1-1 PURPOSE

These Standard References (SRs) covering the technical aspects of locating, drilling, installing, sampling, and decommissioning of monitoring wells have been prepared by the Department of Environmental Protection (DEP) to provide guidance to employees of the Department, consultants, drillers, and members of the regulated community. Monitoring wells may be installed for a variety of reasons including observation of drawdown during a pumping test, determination of groundwater quality, estimation of hydraulic conductivity using permeability tests, determination of ground water flow directions and rates of flow, and monitoring impacts of various activities on the hydraulic head. Some monitoring wells are installed primarily for geochemical monitoring of uncontaminated ground water to serve as baseline data, as well as providing background values against which potential impacts on ground water can be measured. In some cases, chemical sampling is not part of a monitoring program. If ground water chemistry and contaminant characteristics are not matters of concern, then the monitoring well network may be designed with a minimum amount of information, primarily the site geology and hydrology. An in-depth discussion of monitoring well network design can be found in Section 4.1 of these Standard References.

The impetus for writing these SRs came from frequent observations of improperly sited, improperly constructed, and improperly sampled monitoring wells. Such wells do not produce valid data for environmental monitoring purposes. In order to improve the quality of the data collection and of the Department's interpretation of environmental monitoring reports, the writing of these SRs was undertaken.

1.1-2 ORDER OF PRESENTATION

This introductory section contains the full Table of Contents (Section 1.2) and Definitions (Section 1.3). The sections and subsections in the Table of Contents have been assembled in the order in which one typically proceeds when undertaking a hydrogeologic investigation: from site reconnaissance to drilling, to well installation, to ground water sampling. Geophysical techniques, which may be employed during any phase of a site assessment, can be found in a separate section at the end of the document.

It was the authors' decision that each section should be able to stand alone as a reference on a given topic. For that reason, the user will find that this document contains some deliberate redundancies. Cross-references are provided to other sections where a similar subject is discussed.

Most subsections started from a predetermined format: Purpose, Methodology, Problems and Solutions, and References. For editorial simplicity, the figures and tables for each section follow the text rather than being inserted into it. The section on Purpose is designed to present a set of standards to be achieved (i.e., performance standards). The section on Methodology contains some examples of current, acceptable methods for attaining these standards. The methodology does not attempt to be all-encompassing; it seeks to be illustrative. Other techniques which achieve an equivalent degree of compliance with the standard should be equally acceptable.

Each subsection has been assigned its own unique number. Each page within a subsection contains the subsection number, page number, and date. It is anticipated that this document will be expanded and updated in the future by the addition of new subsection pages with new dates. The figures and tables all carry the subsection designation number plus a figure or table number. They also display a consecutive page number. Perhaps an example will clarify this point: the second figure in Section 7.1 would be numbered Figure 7.1-2; the page number might be 24, and the date January 1991.

A loose-leaf format has been chosen to facilitate updating these SRs. The old page should be removed and discarded. The new insert should replace it. It is anticipated that this system may require the use of pages with suffixes such as 4(a), 4(b), etc., so that the original pagination will not be affected.

1.1-3 DEPARTMENTAL USE OF STANDARD REFERENCES

1.1-3.1 Statement by Division of Water Pollution Control (DWPC)

These SRs can serve as a general reference for hydrogeologic investigation techniques. For more specific guidance on submitting hydrogeologic reports, siting discharge points, and designing monitoring well networks in connection with ground water discharge permits, the reader is directed to the following:

- DWPC Policy Memorandum #GW88-1, "Guidelines for siting disposal areas for wastewater treatment plants," 12/1/88.

- DWPC Policy Memorandum #GW88-2, "Monitoring well plan guidelines," 12/1/88.

- "Guidelines for the design, location, operation and maintenance of small sewage treatment plant facilities with land disposal," second draft, January 1988.

Information concerning these publications or other Divisional policies and issues is available from the Ground Water Section at the Division's Boston Office, 1 Winter Street, Boston, MA 02108.

1.1-3.2 Statement by Division of Water Supply (DWS)

Several programs administered by the Division of Water Supply may utilize observation wells or monitoring wells as a means of obtaining information related to the quantity and/or quality of drinking water supplies within the State. These programs include, but are not limited to, Aquifer Land Acquisition, New Source Approval, Water Management Act Permitting, and Water Supply Contamination Correction. For such programs, the Standard References are applicable as general guidance.

To obtain information regarding specific policies and guidance documents, contact the Division of Water Supply at the Department's Boston office.

1.1-3.3 Statement by Division of Hazardous Waste (DHW)

In 1979, Massachusetts enacted M.G.L. c. 21C, the Hazardous Waste Management Act. This act was intended to be equivalent to Subtitle C of the Resource Conservation and Recovery Act (RCRA) passed by the United States Congress in 1976. In 1982, the DEP promulgated regulations (310 CMR 30.000) to enforce the M.G.L. c. 21C statute. This enabled the state to obtain from EPA authorization to implement the RCRA hazardous waste management program in the state.

Ground water protection is a key component of RCRA and M.G.L. c. 21C. Under 310 CMR 30.000, ground water monitoring is required at all hazardous waste disposal facilities and may be required at treatment and storage facilities, if there is a threat to the environment. Ground water monitoring, according to the regulations, can be broken down into two main components:

- Detection monitoring (i.e., detecting a release)
- Compliance monitoring (i.e., assessment and corrective action)

The ground water monitoring requirements of 310 CMR 30.663 are equivalent to the federal RCRA requirements of 40 CFR Part 264, Subpart F. Guidance is available from the U.S. EPA on implementing both detection and compliance monitoring programs under 40 CFR Part 264, Subpart F. The RCRA Ground Water Monitoring Technical Enforcement Guidance Document (TEGD, 1986) discusses site characterization, data collection, well construction, and well system design for detecting a release and assessing the rate and extent of its migration.

The RCRA Corrective Action Plan (June 1988) guidance document published by EPA provides a technical framework for implementing a Compliance monitoring program at RCRA-permitted facilities where a release has occurred. It consists of three phases:

(1) RFI - RCRA Facility Investigation (i.e., assessment; data gathering)

(2) CMS - Corrective Measures Study (i.e., selection of remediation alternatives)

(3) CMI - Corrective Measures Implementation (i.e., implementation of the preferred alternative)

The RCRA Corrective Action Interim Measures Guidance (June 1988) supplements the Corrective Action Plan.

EPA REFERENCES

RCRA Ground Water Monitoring Technical Enforcement Guidance Document Final; EPA/OWPE; September 1986.

RCRA Corrective Action Plan; Interim Final; EPA/530 SW-88-029, June 1988.

RCRA Corrective Action Interim Measures Guidance, Interim Final; EPA/530-SW-88-029; June 1988.

1.1-3.4 Statement by Bureau of Waste Site Cleanup (BWSC)

The Bureau of Waste Site Cleanup is responsible for overseeing the assessment and remediation at oil and hazardous material disposal sites. Subsurface exploration is an integral component of such site assessments and for the evaluation of remedial actions.

1.1-3.4.1 The Massachusetts Contingency Plan (310 CMR 40.000)

In site assessment investigations involving disposal sites, the Massachusetts Contingency Plan (MCP) requires that assessments be performed in phases, incorporating an increasing degree of complexity in each phase as more information is collected and analyzed about the specific site condition. It describes the following investigative phases at a site where hazardous materials may be the constituents of concern to public health and the environment:

- Preliminary Assessment (see MCP 40.541).
- Phase I - Limited Site Investigation (see MCP 40.543).
- Phase II - Comprehensive Site Assessment (see MCP 40.545).
- Phase III - Development of Remedial Response Alternatives and the Final Remedial Response Plan (see MCP 40.546).
- Phase IV - Implementation of the Approved Remedial Response Alternative (see MCP 40.547).
- Phase V - Reserved (see MCP 40.548).

1.1-3.4.2 Long-term Monitoring

It is quite probable that long-term monitoring will be required following the termination of remedial actions or upon the closure of a treatment or disposal facility that might have had an adverse effect upon ground water. Monitoring wells will be needed to detect changes in contaminant levels at a site. It is important that both the site hydrogeology and the contaminant chemistry be understood so that the monitoring well network is effective. For some long-term monitoring, where not all of the preliminary steps have been undertaken, it is important that the monitoring wells are installed properly an that the appropriate construction materials are used.

1.1-4 REVISION AND SUGGESTIONS

This document represents Department of Environmental Protection's current understanding of the art of ground water monitoring. These References will be periodically reviewed by the DEP, and as new techniques are developed and new theories proposed, they will be updated in the light of emerging technologies and revised as appropriate.

The agency invites comments and suggestions related to format, usefulness, and substance. Information on innovative field techniques and suggested updates may be submitted at any time. This information should be sent to:

Department of Environmental Protection
Bureau of Waste Site Cleanup; Policy Branch
One Winter Street, 7th Floor
Boston, MA 02108

ADDITIONAL REFERENCES

Driscoll, F.F., 1986, Groundwater and wells, 2nd edition: St. Paul, MN, Johnson Division, 1089 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, Inc., 604 p.

Journals

Ground Water Monitoring Review: published quarterly by the National Water Well Association, 6375 Riverside Drive, Dublin, Ohio 43107.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

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DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 1.3 DEFINITIONS

SECTION 1.3 DEFINITIONS

Abandoned well - a well whose use has been permanently discontinued; as used in these References it includes a monitoring well, piezometer, or observation well that is no longer suitable for use either for water-level measurements or water quality sampling.

Annular space - see Annulus.

Annulus - the open space between the exterior or the outermost well casing and/or well screen and the wall of the drilled hole, or the space between two or more concentric casings; also, Annular space.

Aquifer - a geologic formation, group of formations, or part of a formation (consolidated or unconsolidated) that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Aquifer, artesian - see Aquifer, confined.

Aquifer, confined - an aquifer saturated with water and bounded above and below by material having a distinctly lower hydraulic conductivity than the aquifer itself.

Aquifer, unconfined - an aquifer partially saturated with water that has no upper confining layer and where the water table is free to rise and fall.

Aquifer test - a test involving the withdrawal or addition of measured quantities of water from or to a well and the measurement of resulting changes in head in the aquifer, both during and after the period of withdrawal or addition. These tests include pumping tests and in-situ permeability tests.

Area of diversion - see Contributing area.

Area of influence - the land that directly overlies and has the same horizontal extent as the part of the water table or other potentiometric surface that is perceptibly lowered or raised by the withdrawal or addition of water. Under pumping conditions, the water in a fully penetrating well ideally flows in from all directions, forming an imaginary cylinder centered about the well and extending throughout the aquifer thickness. This flow pattern applies to both confined and unconfined aquifers. The area of influence, however, is rarely circular in plan view. The size and shape of the area of influence is affected by the slope of the pre-pumping water table or potentiometric surface, by the pumping rate, and by the hydraulic conductivity of the aquifer.

Artesian - synonymous with Confined.

Bentonite - a naturally occurring highly plastic, expansive clay. It is composed largely of the mineral sodium montmorillonite.

Bit - a cutting tool attached to the bottom of the drill stem.

Bridge - an obstruction in the drill hole or annulus, usually formed by caving of the wall of the well bore, by the intrusion of a large boulder, or by improperly placed seals or filter pack materials during well installation. Bridging can also occur in the formation during well development.

Capillary fringe - the zone immediately above the water table where the pressure is less than atmospheric and where all or some of the pore spaces are filled with water.

Capture - the combination of artificially decreasing or increasing water derived from an aquifer that results in a decrease from an aquifer that results in a decrease in the storage of that aquifer.

Capture zone - see Zone of contribution.

Casing - an impervious durable pipe, generally of plastic or metal, installed in a borehole to maintain an opening for the well and to prevent the borehole walls from caving in and closing off the well. Casing may be either temporary or permanent.

Casing, inner - any of the casing rings installed within the outermost casing where casing has been installed as a series of concentric rings.

Casing, outer - the outermost ring adjacent to the borehole wall where casing has been installed as a series of concentric rings.

Cone of depression - the geometric solid that fills the space between the position of the water table or other potentiometric surface after a well has begun discharging and the hypothetical position that the water table or other potentiometric surface would have had if there had been no discharge by the well. For a given aquifer, the cone of depression increases in depth and extent with increasing time until a steady state condition is reached.

Confined aquifer - see Aquifer, confined.

Confining bed - a body of material stratigraphically adjacent to one or more aquifers that has a distinctly lower hydraulic conductivity than the aquifer material.

Contributing area - the land area that has the same horizontal extent as that part of an aquifer, or adjacent areas, from which ground water flow is diverted to the pumping well. The contributing area for a pumping well can be visualized as a two-dimensional area on the land surface. The contributing area and area of influence are not necessarily identical; these areas can be the same only under the hypothetical circumstances where the pre-pumping water table is perfectly flat and all aquifer properties are uniform within the area of influence. When the pre-pumping water table has a hydraulic gradient, as it does under most natural conditions, the contributing area to the well will be distorted to extend to a greater distance on the upgradient side and to a lesser distance on the downgradient side; also, Area of diversion.

<u>Decommission</u> - to plug an abandoned well so that it will not serve as a conduit for movement of water to or from the well or between water-bearing zones; often preceded by cleaning a well, ripping or removing well casing if necessary and/or practical. See plug, plugging

<u>Department</u> - the Massachusetts Department of Environmental Protection (DEP).

<u>Development</u> - see Well development.

<u>Dig-Safe</u> - a company set up by gas and electric utilities that should be contacted to determine the location of underground utilities in public right-of-way (in MA: 1-800-322-4844, in ME, NH, VT: 1-800-225-4977). Dig-safe requires at least three days notice and may or may not trace lines across private property.

<u>Drawdown</u> - the effect of lowering a water table or other potentiometric surface a vertical distance with respect to its initial position; it is caused by pumping water from an aquifer.

<u>Drilling fluid</u> - a water- or air-based fluid used in the well drilling operation to remove cuttings from the hole, clean and cool the bit, reduce friction between the drill string and the sides of the hole, or seal the sides of an uncased borehole.

<u>Filter pack</u> - the smooth, uniform, silt-free, well-rounded, and usually siliceous sand or gravel placed in the annulus of a well between the borehole wall and the well screen or intake zone in order to facilitate flow toward the well intake and to prevent formation material from entering or clogging the screen; also, Gravel pack or Formation stabilizer.

<u>Formation</u> - a unit of consolidated or unconsolidated material that has distinct lithological characteristics.

<u>Formation stabilizer</u> - see Filter pack.

<u>Gravel pack</u> - see Filter pack.

<u>Ground water</u> - water occurring beneath the ground surface in the saturated zone.

<u>Ground water divide</u> - a hypothetical vertical boundary across which ground water flow does not occur; ground water gradients on both sides of the boundary result in ground water flow away from the divide.

<u>Ground water contour</u> - a line connecting points of equal hydraulic head, based on the elevation of the water surface in wells screened at approximately the same elevation (mean sea level) with screens approximately the same length.

<u>Grout</u> - a thick fluid mixture of neat cement and water of a consistency that can be forced through a pipe and placed at a required depth or zone in a monitoring well. Various additives, such as sand, bentonite, and hydrated lime, may be in the mixture to meet certain requirements.

Grouting - the operation by which grout is placed as a permanent seal between the outer casing and the sides of the borehole or in the openings between concentric rings of inner casing or in the opening between an inner and outer casing; also, as used in these References, the act of sealing, or plugging, a decommissioned monitoring well, observation well, or piezometer.

Head, hydraulic (h) - the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. The hydraulic head is the sum of the elevation head (h_e) and the pressure head (h_p); that is, $h = h_e + h_p$. Head, when used alone, is understood to mean hydraulic head. The head is proportional to the fluid potential; therefore the head is a measure of the potential. Head has the units of length.

Hydraulic conductivity (K) - the rate at which a homogeneous fluid at the existing kinematic viscosity will move in a unit of time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow through an isotropic, porous medium. Hydraulic conductivity has the units of length/time (L/T).

Hydraulic gradient - the change in hydraulic head per unit of distance in a given direction. It provides the driving force for groundwater movement and it has horizontal and vertical components. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head. Hydraulic gradient has the units of length/length (L/L). It is estimated by taking the difference between two points (along the flow path) and dividing by the distance between the points.

Infiltration - the flow of water or other fluids downward from the ground surface through the unsaturated zone.

Monitoring well - see Well, monitoring.

Observation well - see Well, observation.

Organic vapor analyzer - a portable instrument designed to determine the presence and relative concentration of volatile organic vapors. Common detection methods include photoionization (PID) and flame ionization (FID). NOTE: The use of this terminology refers to a generic class of portable instrumentation and should not be construed as an endorsement of specific brands or trade names of equipment.

Overburden - the unconsolidated material overlying bedrock, such as clay, silt, sand and gravel, either transported or formed in place. Overburden can be either native, imported fill, or material that has been reworked in place; also, Unconsolidated formation.

Phreatic zone - see Zone, saturated.

Permeability (intrinsic permeability) (k) - a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone that is dependent upon the size and shape of its pores and is independent of the nature of the liquid and of the force field causing movement. Permeability has the units of length squared (L).

Piezometer - a small-diameter well designed to measure the hydraulic head (water level elevation) at a specific point in the saturated zone beneath the ground surface. A piezometer has a short screen that is positioned entirely within the saturated zone of an unconfined or confined aquifer.

Plug, plugging - the proper closure of an abandoned well or boring by procedures that will permanently seal the well from the aquifer and from contamination by surface drainage; where the well penetrates multiple or confined aquifers, it will permanently seal off and prevent flow between aquifers.

Pollution - alteration of the chemical, physical, biological, or radiological integrity of the environment.

Porosity (n) - the ratio of the volume of total void space to the total volume of a rock or unconsolidated deposit. It may be expressed as a decimal fraction or as a percentage. The units of porosity are dimensionless.

Porosity, effective (n_e) - the amount of interconnected pore space available for fluid transmission in a rock or unconsolidated deposit, expressed as a percentage of the total volume occupied by the interconnecting interstices. When used alone in this document, porosity refers to effective porosity.

Potentiometric surface - as used in this document, a hypothetical surface representing the hydraulic head of ground water in either a confined or an unconfined aquifer at a particular elevation in the aquifer; synonymous with piezometric surface.

Private water supply well - see Well, domestic water.

Pump test (pumping test) - a test conducted to determine aquifer or well characteristics and properties; see Aquifer test.

Quick condition - a condition of soil in which an increase in pore-water pressure decreases particle-to-particle attraction and reduces significantly the soil's shear strength; also, Liquefaction.

Radius of influence - the horizontal distance between a pumping well and the outer limit of the cone of depression.

Refusal - a condition that occurs when drilling or excavating equipment is unable to penetrate the ground a substantial distance in a reasonable period of time. In glaciated regions, unless there is supporting visual or geophysical evidence, it is often difficult to determine whether refusal has taken place at the bedrock interface or at a glacial erratic. Refusal is dependent upon the size and strength of the equipment used.

Saturated zone - see Zone, saturated.

Screen - see Well Screen

Seal, annular - the watertight materials placed in the drill hole between an outer casing and the borehole wall, between an inner casing and an outer casing, or between two or more inner casings, to prevent the inflow and movement of surface water or ground water into the annulus, or to prevent the outflow or movement of water under artesian or hydrostatic pressures through the annulus.

Seal, divider - a layer of bentonite or other impervious material placed on top of the filter pack and below the annular seal.

Seal, surface - the materials placed in the top four feet of the annular space that are designed to prevent the infiltration of surface water into the annular space. If an above-ground protective casing is installed, the surface seal is mounded at the land surface to conduct surface water runoff away from the well.

Sieve analysis - the determination of the dry particle-size distribution of a soil, sediment, or rock by measuring the percentage (by weight) of the particles that will pass through or be retained on standard sieves with openings of various sizes.

Specific discharge (q) - the rate of discharge of ground water per unit area measured at right angles to the direction of flow. Specific discharge has the dimensions of velocity (L/T), as follows:

$$q = \frac{Q}{A}$$

where Q equals total discharge, or total flux, through area A. Specific discharge is a precise term and is preferred to terms involving "velocity" because of possible confusion with actual fluid velocity through the pore space.

Specific Retention - is the ratio of the volume of water which the rock or soil, after being saturated, will retain against the pull of gravity to the volume of the rock or soil.

Specific yield (S_y) - a change in storage per unit area of unconfined aquifer as the result of a unit change in head. It is equal to porosity minus specific retention. The units of specific yield are dimensionless.

Static water level - the level of water in a well that is not being influenced by the addition or withdrawal of water into the aquifer.

Storage coefficient (S) - the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In a confined water body, the water derived from storage with decline in head comes from expansion of the water and compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined water body, the amount of water derived from or added to the aquifer by the processes of expansion and contraction is negligible compared to that involved in gravity drainage or filling of pores; hence, in an unconfined water body, the storage coefficient is virtually equal to the specific yield.

Test hole - a drilled borehole used solely for geotechnical or geological purposes; also, Test boring.

Test pit - any excavation made with a shovel or a backhoe for the purpose of visually examining the characteristics of subsurface formations; due to the large volume of disturbed soil in a test pit, it should not be used as a location for a monitoring well.

Transmissivity (T) - the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths. The units of transmissivity are length squared divided by time (L/T).

Tremie pipe - a device, usually a small diameter pipe, that carries grout, bentonite pellets or gravel pack materials to the bottom of a borehole and allows pressure grouting or gravel packing from the bottom up without introduction of appreciable air pockets or bridging.

Uncased test hole - a test hole from which casing has been removed or in which casing has not been installed.

Unconfined aquifer - see Aquifer, unconfined.

Unconsolidated formation - the unlithified geologic materials or deposits such as sand, gravel, clay, and till overlying bedrock, either transported or formed in place; also, Overburden.

Unsaturated zone - see Zone, unsaturated.

Vadose zone - see Zone, unsaturated.

Velocity, average interstitial - (Av. v_i) - the average volume rate of flow of a fluid through the pore spaces. Average interstitial velocity has the units of length/time (L/T).

Water table - the upper surface of an unconfined aquifer at atmospheric pressure. It is defined by the levels at which water stands in wells that penetrate the saturated zone just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground water flow exists; also, Potentiometric surface.

Water table aquifer - see Aquifer, unconfined.

Well - a hole drilled or driven into the ground, capable of withdrawing water from the aquifer (1) to provide water for human consumption or other beneficial uses, (2) to obtain geologic information about an aquifer, (3) to monitor the quality or quantity of water, (4) to obtain ground water samples, or (5) to utilize the geothermal properties of earth formations.

Well, abandoned - see Abandoned well.

Well, artesian - a well deriving its water from a confined aquifer. The water level in the well stands above the top of the confined aquifer it taps. This term applies to both flowing and non-flowing wells. (In this document the term is not given a second meaning, used by well drillers, referring to any well terminating in bedrock.)

Well, dewatering - a well constructed for the purpose of lowering the ground water surface, either temporarily or permanently.

Well, domestic water - a water well providing water for human use from other than a public water supply system; a well for the watering of livestock, poultry, farm and domestic animals used in operating a farm; a well for the irrigation of small gardens or farms.

Well, monitoring - a cased well installed for the purpose of obtaining representative samples of ground water for water quality analysis, monitoring for the possible presence of contaminants, or taking water level measurements.

Well, observation - a cased well installed for the purpose of monitoring water levels.

Well, open hole - a well formed by drilling a hole into consolidated rock formations, such as granite or sandstone, and finished with no casing or screen opposite the water-yielding portion of the aquifer.

Well, public water supply - a well that is part of a system for the provision to the public of piped water for human consumption, that has at least fifteen (15) service connections or regularly serves an average of at least twenty-five (25) individuals daily at least sixty (60) days of the year (310 CMR 22.00).

Well, recovery - a well designed to control and hydraulically capture separate phase liquids or ground water containing dissolved contaminants.

Well development - the act of mitigating the effects of alteration to the geologic formation caused by drilling and well installation procedures (e.g., smearing or skim coating the borehole walls, bridging of the natural formation or filter pack, or introduction of water or other fluids not originally derived from the aquifer being developed), and increasing the porosity and permeability of the materials surrounding the intake portion of the monitoring well to ensure hydraulic communication with the aquifer.

Well driller - a person engaged in the business of drilling or driving wells; said driller must be currently registered with the Water Resources Division, Department of Environmental Management, Executive Office of Environmental Affairs, Commonwealth of Massachusetts.

Well operator - a person who undertakes to maintain, use, and/or monitor a well; the term describes a person who does not own the land on which a specific well has been installed.

Well owner - a person who owns the land used for any purpose on which a well has been installed. The well owner is responsible for maintaining the well in good condition and decommissioning it when it is no longer used (i.e., becomes an abandoned well). A well owner may also be the well operator of a different or another well located on land that he does not own.

Well point - a well screen device, equipped with a point at one end, that is meant to be driven into the ground until it reaches the saturated zone.

Well screen - the intake section of a well that obtains water from an aquifer and serves as a filtering device to keep sediment from entering a water well.

Zone, saturated - that part of the water-bearing material in which ideally all voids, large and small, are filled with water under pressure greater than atmospheric; also, Phreatic zone.

Zone, unsaturated - the zone between the land surface and the water table. It includes the capillary fringe. Characteristically, this zone contains liquid water under less than atmospheric pressure, and water vapor and air or other gases generally at atmospheric pressure. Perched water bodies may exist within the unsaturated zone; also, Vadose zone and Zone of aeration.

Zone I - the protective radius required around a public water supply well or wellfield (310 CMR 22.00).

Zone II - that area of an aquifer which contributes water to a well under the most severe pumping and recharge conditions that can be realistically anticipated (180 days of pumping at safe yield, with no recharge from precipitation). It is bounded by the ground water divides that result from pumping the well, and by the contact of the aquifer with less permeable materials such as till or bedrock. In some cases streams or lakes may act as recharge boundaries. In all cases, Zone II shall extend upgradient to its point of intersection with prevailing hydrogeological boundaries (a groundwater flow divide, a contact with till or bedrock, or a recharge boundary) (310 CMR 22.00).

Zone III - that land area beyond the area of Zone II from which surface water and ground water drain into Zone II. The surface water drainage divides as determined by topography will be used to delineate Zone II. In some locations, where surface and ground water are not coincident, Zone III shall consist of both the surface drainage and the ground water drainage areas (310 CMR 22.00).

Zone of contribution - the three-dimensional volumetric portion of an aquifer from which ground water flow is diverted to a pumping well; also, Capture zone and Zone of diversion.

Zone of diversion - see Zone of contribution.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 2.1 RECONNAISSANCE SURVEYS

SECTION 2.1
RECONNAISSANCE SURVEYS

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SECTION 2.1
RECONNAISSANCE SURVEYS

2.1-1 PURPOSE

Reconnaissance surveys are carried out for a number of environmental reasons:

- o To assess the suitability of the ground water or surface water at a site as a source of water supply for human consumption, fighting fires, non-contact cooling or other industrial process water, irrigation or other agricultural purposes.
- o To assess the suitability of a site for the storage, treatment or disposal of solid waste, sludges, or hazardous materials.
- o To assess the impact of an existing or proposed development upon a wetland area or a marine estuary.
- o To determine whether or not contamination of air, soil, ground water or surface water at the site is attributable to past or present waste disposal practices.
- o To determine whether or not a site is located within the Aquifer Protection Zone (Zone II) of a public water supply.
- o To determine the natural quality of ground water as a baseline reference in case of future contamination problems.

The purpose of a reconnaissance survey is to collect and synthesize the available historical, environmental, physical, and chemical information about a location to be studied prior to undertaking an exploratory field program. A thorough survey can usually develop a useful amount of information about a site, including: its geology, ground water and surface water hydrology, drainage patterns, topography, past and present land use, location of underground and aboveground utilities, buildings, and storage areas. Collection of this information can identify data gaps and assist in the development of a cost-effective field program.

On-site subsurface investigations using test pits, boreholes or monitoring wells generally are not part of a site reconnaissance program. However, if the results of previous sampling efforts are available, they should be utilized. All of this information can assist in the development of a more focused investigation at the start of an exploratory field program, potentially eliminating duplication of effort and identifying specific problem areas.

At locations where contamination is suspected or known to be present, the reconnaissance survey should be carried out in such a way that there is minimal risk of exposure to the personnel conducting the investigation. A preliminary Health and Safety Plan should be prepared which emphasizes the importance of precautionary and preventative measures. Most of the investigation should be conducted off-site or in the areas where the risk of exposure is minimal. A good health and safety training program should distinguish between the low-risk nature of a reconnaissance investigation and the higher-risk nature of a full-scale program of exploration with drill rigs, monitoring wells and collection of environmental samples (see Section 2.3).

Under the Massachusetts Contingency Plan (310 CMR 40.000), two types of reconnaissance investigations are listed: a Preliminary Assessment (Sec. 40.541) and a Phase I - Limited Site Investigation and Report (Sec. 40.543). A Preliminary Assessment is described as an initial evaluation to determine whether or not the location is a disposal site, whether a short-term measure is necessary, and whether further remedial response is necessary. It includes researching and assembling existing data and conducting at least one reconnaissance visit. A Phase I - Limited Site Investigation and Report is intended to confirm whether or not the location is a disposal site, if this was not established in the Preliminary Assessment. If it is a disposal site, the report must provide information necessary for DEP to classify the site as a priority or a non-priority disposal site. The Phase I - Limited Site Investigation Report, therefore, must include a detailed history and description of the location. Site characterization of waste sources is expected to be investigated using field screening techniques, geophysical methods, and field sampling of various media and subsequent laboratory analysis.

Depending on the scope of the project, a reconnaissance survey may involve some or all of the following elements:

- A field visit to the site to confirm or refine the preliminary map(s); to familiarize the project team with the site conditions, including topography, drainage, and vegetation; to evaluate site access; to locate overhead and underground utilities; to determine if land use activities have changed; and to evaluate other factors that might affect the field program.

- Literature search of available data on the geology, hydrology, historical land-use, and information obtained during previous investigations.

- Terrain analysis based on a review of topographic maps, aerial photos, and, if possible, remotely-sensed imagery.

- Construction of a preliminary base map for the site and/or the region.

- Compilation of available geologic, topographic, and hydrologic data onto the base map(s).

- Assessment of on-site hazards for development of a site specific Health and Safety Plan, if necessary.

- Field observation of on-site and adjacent industrial processes, and/or hazardous material use, storage, treatment, or disposal.

- o Development of a field investigation program based on the observed and anticipated hydrogeologic conditions and other site-specific factors.

Figure 2.1-1 is a flow chart of the elements of a reconnaissance investigation.

2.1-2 METHODOLOGY

2.1-2.1 Literature Search

A literature search involves identifying available published information for a specific area, including maps, reports, and theses. There are numerous sources of information, including the United States Geological Survey (U.S.G.S.), state agencies, local agencies, universities, and public libraries. At the present time, there is no central statewide repository in the Commonwealth of Massachusetts for information on 21E site assessments, RCRA permits, NPDES discharge permits, ground water discharge permits, and other regulated activities. Consequently, the investigator may have to seek out several different sources of information to compile a comprehensive database on a specific project. Information that may be useful for a reconnaissance investigation includes topographic, geologic, and hydrologic data; aerial photos; data from geotechnical projects; bridge borings; permits for former or existing activities; previous investigations; and historical land use. Potential sources for much of this information are presented below. Figure 2.1-2 is a flow chart depicting the present organizational structure of the Massachusetts' DEP, which may be helpful in identifying where certain files, records and information may be located within the department.

Information can be obtained from the following sources:

2.1-2.1.1 Published Bibliographies.

(a) Annotated Groundwater Bibliography Covering the Northeast

Published in 1982 by the Massachusetts Audubon Society, Lincoln, Massachusetts. References on general and technical ground water issues, including books, reports, journals, technical articles, and conference proceedings.

(b) Massachusetts Hydrologic Matrix

Published in 1982 by the Massachusetts Department of Environmental Quality Engineering, (now DEP), Division of Water Supply, Boston, Massachusetts. Summarizes many sources of information available from the U.S.G.S. on subsurface geology and hydrogeology in Massachusetts. Includes geologic quadrangle maps, project bulletins, and miscellaneous investigations. Also contains some references to municipal, industrial, and academic reports on aquifers.

2.1-2.1.2 Geologic Maps.

Geologic maps of interest in reconnaissance investigations include surficial soils, bedrock maps, and hydrologic atlases. Geologic maps depict, in plan view, contacts between the surface exposures of various soil deposits or rock formations. The scale, detail, and accuracy of geologic maps will vary depending on the intensity of the field investigation and the amount of exposure. Geologic maps are available in a wide range of scales. Table 2.1-1 is a guide to common map scales and related information. Tables 2.1-4 and 2.1-6 contain a list of sources of information that may be used in compiling geologic maps; Table 2.1-7 contains a list of Geoscience Agencies for 50 states and the territory of Puerto Rico.

(a) Bedrock Geologic Maps

Bedrock maps contain information on rock types, ages, and structural features such as faults, joints, and foliation. Bedrock maps are available from several sources including the U.S.G.S., graduate theses, and miscellaneous publications available at university and public libraries. A map of the bedrock geology of the Commonwealth of Massachusetts, at a scale of 1:250,000, has been published by the U.S.G.S. Additionally, U.S.G.S. has published maps of the bedrock geology of numerous quadrangles in Massachusetts.

(b) Surficial Geologic Maps

Surficial geologic maps show the distribution of unconsolidated materials on the ground surface. Surficial maps depict the types of soil materials, as well as directions of glacial movement, locations of borrow pits, and areas where bedrock is exposed or located within approximately 10 feet of the ground surface. The mapped soil units may include outwash deposits, glacial till, marine clays, organic deposits, and man-made fills. An official, regional surficial map for Massachusetts is not presently available, but surficial geologic maps of numerous quadrangles in Massachusetts have been completed by the U.S.G.S. As with bedrock maps, additional sources of information include graduate theses and miscellaneous publications available at local universities and public libraries.

2.1-2.1.3 Hydrologic Information.

(a) U.S.G.S. Hydrologic Atlases and Basic Data Reports

The Water Resources Division of the U.S.G.S. has published a series of atlases for most of the major river basins in Massachusetts. These reports present information on the surface and ground water resources in the basin. The Hydrologic Atlas includes information on the following items:

- Basin boundaries
- Precipitation
- Ground water levels

- o Basic data well locations
- o Location of low, moderate, and high yield zones in surficial aquifers

(b) DEP Water Supply Protection Atlas

A water supply protection atlas has been compiled by DEP's Division of Water Supply. The atlas consists of a series of four acetate overlays to be used with the 1:25,000-scale U.S.G.S. topographic quadrangle maps. The overlays depict the following information:

- o Public water supplies: ground water and surface water sources

- o Aquifer information: location and characterization of yield of known aquifers

- o Drainage divides: major rivers and sub-basins

- o Waste sources: surface impoundments, landfills, auto junkyards, road salt storage areas, and NPDES discharge locations.

(c) Zone of Contribution (Zone II), as Defined by DEP

As these zones of contribution are officially mapped and approved, they will provide significant information about the protected area of contribution around a public water supply.

2.1-2.1.4 Other Sources of Information

(a) Soil Conservation Service (SCS) Soil Surveys

Some consultants attempt to use SCS information in environmental assessments. However, in the opinion of the Department, the SCS classification system is not suitable for use in hydrogeologic studies. Soil survey maps produced by the Soil Conservation Service of the U.S. Department of Agriculture are generally plotted on an aerial photo base. These surveys are usually prepared on a county basis and contain information on soil drainage conditions, slopes, and shallow ground water.

(b) DEP Files and Reports

Other significant sources of hydrogeologic information are the reports prepared by consultants for municipalities, DEP, and the private sector in connection with development of public water supplies, sewerage systems, building construction, and contamination investigations. Many of these reports are available at the regional DEP offices or the DEP office in Boston. Individuals interested in reviewing these files must make an appointment in advance with the respective DEP office. Reports relating to sites on the National Priorities List are put on file at local libraries and are available for review at these locations. There is no central bibliography of these reports at this time.

(c) Environmental Protection Agency (EPA) Library

The regional office of EPA has a well-stocked reference library of U.S. Government environmental publications and reports. The library is located at One Congress Street, 11th floor, Boston, Massachusetts, Tel. (617) 918-1990.

(d) Aerial Photographs

Inspection of aerial photos is an effective and economical way to become familiar with a site. Stereo pairs of aerial photos can be viewed with a stereoscope to produce a three-dimensional image of the ground surface; the view is similar to flying over the site in an airplane. Various aspects of site geology, vegetation, hydrology, and landforms may be interpreted from aerial photos. The Massachusetts Department of Public Works maintains a library of stereo pair aerial photos with coverage of most of the state at 10-year intervals. Individuals who wish to view the photos must make an appointment with the Office of Transportation. They are located in the Photogrametric Section, Geodetic Survey, Massachusetts Department of Public Works, 10 Park Plaza, Boston. Photos cannot be removed from the premises. Aerial photo coverage is also available from some municipalities.

(e) Bridge Borings

Bridge boring information is available for inspection at the office of the Massachusetts Department of Public Works, 10 Park Plaza, Boston. Individuals wishing to view the borings must call ahead for an appointment.

(f) HUD Flood Insurance Maps

These maps have been prepared for almost all communities. They show flood-prone areas.

(g) Sanborn Fire Insurance Maps

These maps are compiled periodically by a private firm. Where available they can provide a historical record of facility layouts.

2.1-2.2 Map and Remote Sensing Interpretation

A review of a series of historical photographs and maps can be used to observe how land use activities have changed over time and to locate old lagoons, dumps, and other waste disposal areas.

2.1-2.2.1 U.S.G.S. Topographic Maps

Topographic maps display landforms, drainage, man-made features, vegetation, and contour lines. Contour lines connect points of equal elevation above sea level. In addition, spot elevations are depicted at the tops of hills, road intersections, and survey points. On U.S.G.S. topographic maps, specific colors are used on all maps to depict various features:

Brown	contour lines
Blue	drainage, water bodies
Black	boundaries, bench marks, roads, and mines
Green	trees, brush, and crops
Red	highways, fences, and survey lines
Pink	closely spaced buildings in urban areas
Purple	revisions made from aerial photographs that have not been field checked

U.S.G.S. topographic maps for Massachusetts are available at various scales including 1:24,000, 1:25,000, and 1:62,500. Exact positions of latitude and longitude are shown along the map margins. Each map or quadrangle has a name that is unique to that quadrangle, generally corresponding to a town located in the quadrangle. In Massachusetts the U.S.G.S. has recently published a series of metric 7.5-minute maps at a scale of 1:25,000 for the entire state. Very recently, double quads (7.5 minutes x 15 minutes) have been published for certain parts of the state. At the base of the map is a graphic scale in feet, miles, meters, and kilometers. If the map is photocopied, enlarged, or reduced, the graphic scale should also be copied to maintain the accuracy of the scale of the reproduction of the original map.

2.1-2.2.2 Remote Sensing

Remote sensing can be used in the interpretation of site geology and drainage. Infrared and multi-spectral imagery can be used to identify thermal gradients, which may be indicative of surface water pollution, subsurface seepage, or stressed vegetation. Table 2.1-2 lists the common forms of remote sensing imagery. Table 2.1-3 summarizes the uses of remote sensing imagery used in hydrogeologic and site investigations. Conclusions drawn from photo interpretation should be verified on the ground during a site visit. Sources of remote sensing imagery are listed in Table 2.1-5.

2.1-2.3 Historical Review

A historical review can provide information about the suitability of a site for its intended purpose or the potential degree of contamination that might be associated with the land and the ground water. Potential sources of historical information should be consulted. These include, but are not limited to, previous owners and employees, neighbors, municipal records and officials, newspaper articles and photographs. Section 2.2-4.1.1 lists the MCP requirements for the history of a location.

2.1-2.4 Physical Characterization of a Location

It is extremely important that the location of the reconnaissance investigation be identified on plans, both regionally and specifically. A U.S.G.S. topographic quadrangle is usually sufficient to provide the general locus of the area being investigated. Geographical coordinates (latitude and longitude or UTM grid coordinates) will provide a universally accepted description of the precise area under investigation. The amount of detail included in the physical characterization will depend on the objective(s) of the investigation and the type of information needed to plan the next phase of a hydrologic investigation. Physical features that might be significant during a reconnaissance investigation include:

- Site access
- Site topography and drainage
- Significant cultural features
- Vegetation
- Geology
- Hydrologic features
- Wetlands
- Adjacent land use
- Utility locations and easements

Section 2.2-4.1.2 lists the MCP requirements for the physical characterization of a location.

2.1-2.5 Base Map Preparation

A fundamental part of a reconnaissance program is the preparation of a preliminary base map. The extent of area covered by this base map will depend on the nature of the investigation. The scale of the map will be dependent upon the size of the area and the type and detail of available information. A regional map may have a scale on the order of a mile to the inch, while a site-specific map may have a scale of 100 or 200 feet to the inch. The base map can be prepared from an air photo, an enlarged U.S.G.S. topographic map, a local assessor's map, or a site survey. If possible, the base map should contain the following information:

- graphic scale
- north arrow, indicating true north
- source(s) of map base

- o significant cultural features
- o site features including drainage, topography
- o property boundaries
- o site boundaries
- o underground and overhead utilities
- o existing wells, drains, and other underground features
- o legend
- o notes

Following the preparation of a base map, it may be helpful to compile the existing geologic and hydrologic information onto various base maps, depending upon the detail and accuracy of the existing information. During a subsequent site visit, it is helpful to have geologic and hydrologic maps available so that information shown on the base map can be easily confirmed or refined.

2.1-2.5.1 Site Visit

A site visit should be performed after the compilation of available information and preparation of the preliminary base map. The primary purpose of a site visit is to confirm, supplement, or modify the existing information about the site. The following items should be considered during a site visit.

(a) Site Access

Fences, roads, topography, vegetation, subsurface or overhead utilities, wet areas, and other factors that may affect a subsurface exploration programs.

(b) Site Topography and Drainage

General topography and drainage as they relate to site hydrogeology and access.

(c) Significant Cultural Features

Presence of buildings, overhead and underground utilities, storm drains, buried tanks, parking lots, or roads that would influence access for a subsurface boring program.

(d) Vegetation

Describe surface vegetation (i.e., wooded, grassy, or marshy) and how it relates to access for a filed investigation program. Determine if the pattern of vegetation is consistent with hydrogeologic interpretations (i.e., wetland vegetation where ground water discharge occurs). Look for evidence of stressed vegetation that might relate to contamination of the surface water, ground water, or soil.

(e) Geology

Assess whether landforms, soil characteristics, and rock outcrops are consistent with available data. Look for sinkholes, gullies, and excavations for information on subsurface conditions. Locate outcrops and note the rock type, degree of weathering, and structure. Describe the surficial geology, frequency and size of boulders, presence and character of artificial fill, and the presence of organic soils.

(f) <u>Hydrologic Features</u>

Locate surface water bodies, wells, springs, and wetlands. Estimate surface and subsurface flow directions. Estimate elevation of water surface in streams, below bridges, and in ponds. Estimate the depth to the water table.

(g) <u>Wetlands</u>

Look for wetland areas that will be subject to the jurisdiction of the local Conservation Commission under M.G.L. c131, sec. 40, or the U.S. Army Corps of Engineers under Section 404 of the Clean Waters Act, as amended.

(h) <u>Waste Information</u>

Describe the presence and condition of drums, barrels, other storage containers, and disposal areas. Record evidence of spills, soil discoloration, leachate breakout, seeps, fill materials or odors. Locate and describe the condition of tanks, waste water systems, pits, lagoons, and disposal areas.

(i) <u>Facility Operations</u>

If the site includes an operating facility, the site reconnaissance should include an interview with individuals responsible for operation of this facility, followed by an evaluation of the status of the existing operation of the site.

(j) <u>Land Use</u>

Obtain as much information as possible about past and present land use activities at and near the site. If possible, obtain the names of employees or neighbors knowledgeable about the site. Verify that the use of adjacent land is consistent with available data. Evaluate the relative significance of abutting up-gradient and down-gradient environmental receptors. Determine if adjacent land uses or activities might alter ground water flow directions or present possible sources of contamination. Identify sensitive environmental receptors.

It is important to maintain good notes during a site visit. Examples of site reconnaissance checklists that can be used during a site visit are included in Appendix A and B. It is most useful to make notations directly on a site base map. Geologic contacts can also be confirmed during a site visit.

A pocket tape recorder may be useful for dictating notes and recording conversations with individuals associated with the site. If a tape recorder is used, the notes should be transcribed immediately upon return to the office to avoid accidental data loss.

2.1-2.5.2 Map Revision

Existing data should be revised and updated following the completion of a reconnaissance site investigation. If not already completed, the pertinent geologic, hydrologic, cultural, and land use information should be compiled onto the various base maps. Once this is complete, a site-specific investigation program can be developed based on a review of all accurate, available data.

2.1-3 PROBLEMS AND POSSIBLE SOLUTIONS

2.1-3.1 Restricted Site Access and Uncooperative Landowners

Frequently, landowners become increasingly wary or uncooperative during a field investigation program. It is important to obtain as much detailed information as possible during a preliminary site visit in case future access is restricted. Additionally, areas critical to understanding the site should be investigated as early as possible in the program in case access is eventually restricted.

In some cases, it may not be possible to perform a thorough site investigation due to limited or prohibited access. A file review of local sites and field visit to adjacent sites may be helpful in evaluating the available data. In cases where landowners are uncooperative, local and state officials may be of some assistance in persuading landowners to permit site access.

2.1-3.2 Lack of Available Data

In some areas, little or no data are available about a site, making a preliminary assessment of geologic and hydrologic conditions extremely difficult. In this case, a thorough review of the regional data and a detailed site visit are recommended. Assistance from experienced geologists and engineers during a site visit may be helpful in identifying the actual site conditions. If the available data are very sparse and the site visit is limited, it will be advisable to perform a phased investigation program consisting of surface geophysical investigations and/or preliminary test pits and borings before planning the full-scale site investigation.

2.1-3.3 Weather Conditions

Snow cover, high water and rain may significantly hamper a thorough site visit. Outcrops, excavations, man-made features, and even odors may be obscured by adverse weather conditions, severely limiting the effectiveness of a preliminary site visit. If possible, site visits should be planned for a time when all the significant features are fully accessible.

REFERENCES

American Geological Institute, 1990, Directory of Geoscience Organizations-U.S. State Surveys: in Geotimes, October, 1990, V. 35, n.10.

Hunt, R.E., 1984, Geotechnical engineering investigation manual: New York, N.Y., McGraw-Hill, 683 p.

SECTION 2.1
RECONNAISSANCE SURVEYS

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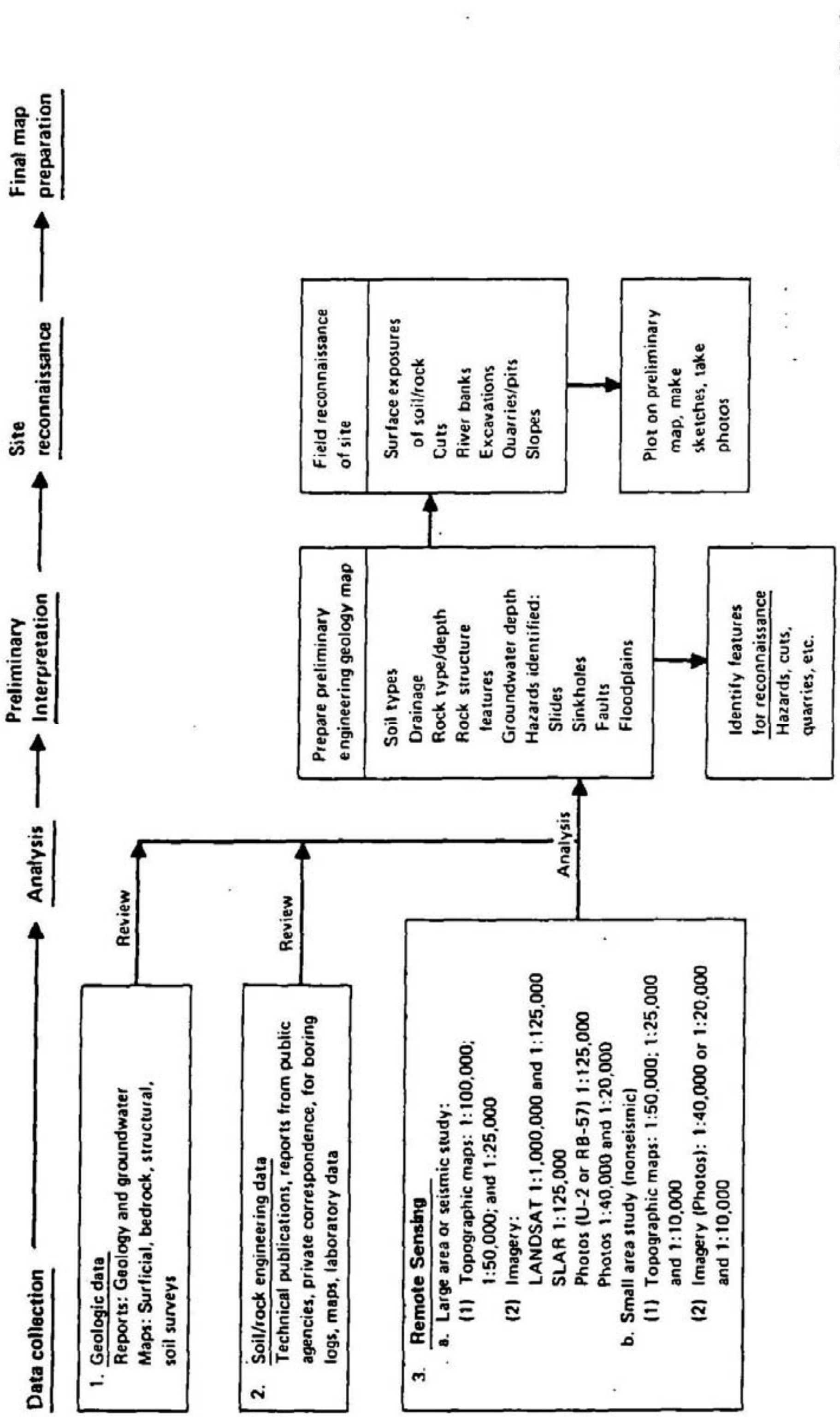

Source: Hunt (1984)

Figure 2.1-1
Elements of a Reconnaissance Study.

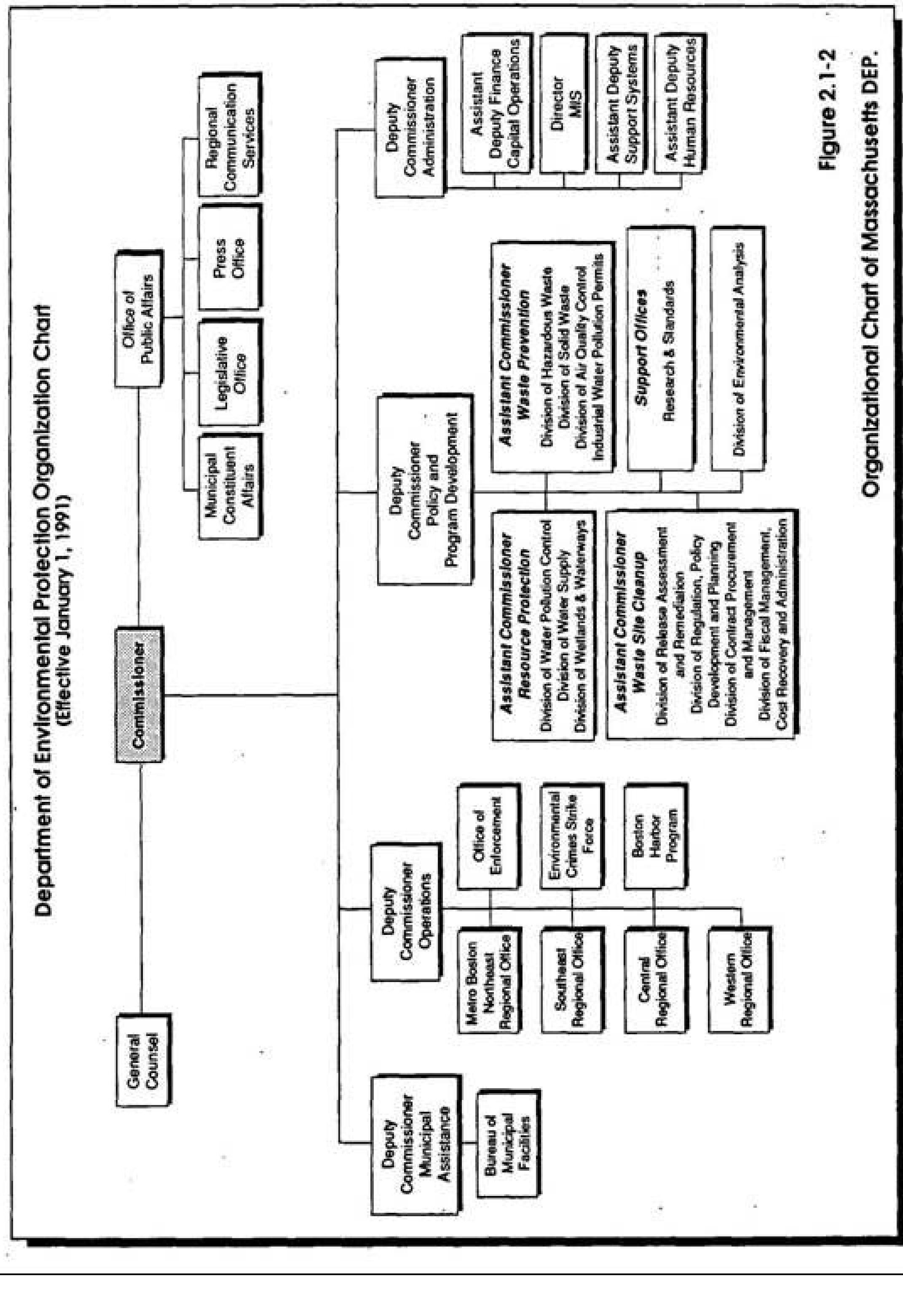

Figure 2.1-2
Organizational Chart of Massachusetts DEP.

GUIDE TO MAP SCALES

Scale	Feet per Inch	Inches per 1000 feet	Inches per mile	Miles per Inch	Meters per Inch	Acres per square inch
1:500	41.67	24.00	126.72	0.008	12.70	0.040
1:600	50.00	20.00	105.60	0.009	15.24	0.057
1:1000	83.33	12.00	63.36	0.016	25.40	0.159
1:1200	100.00	10.00	52.80	0.019	30.48	0.230
1:1500	125.00	8.00	42.24	0.024	38.10	0.359
1:2000	166.67	6.00	31.68	0.032	50.80	0.638
1:2400	200.00	5.00	26.40	0.038	60.96	0.918
1:2500	208.33	4.80	25.34	0.039	63.50	0.996
1:3000	250.00	4.00	21.12	0.047	76.20	1.435
1:4000	333.33	3.00	15.84	0.063	101.60	2.551
1:5000	416.67	2.40	12.67	0.079	127.00	3.986
1:6000	500.00	2.00	10.56	0.095	152.40	5.739
1:7920	660.00	1.515	8.00	0.125	201.17	10.000
1:8000	666.67	1.500	7.92	0.126	203.20	10.203
1:9600	800.00	1.250	6.60	0.152	243.84	14.692
1:10000	833.33	1.200	6.336	0.158	254.00	15.942
1:1200	1,000.00	1.000	5.280	0.189	304.80	22.957
1:1500	1,250.00	0.800	4.244	0.237	301.00	35.870
1:15840	1,320.00	0.758	4.000	0.250	402.34	40.000

Scale	Feet per Inch	Inches per 1000 feet	Inches per mile	Miles per Inch	Meters per Inch	Acres per square inch
1:19200	1,600.00	0.625	3.300	0.303	487.68	58.770
1:20000	1,666.67	0.600	3.168	0.316	508.00	63.769
1:21120	1,760.00	0.568	3.000	0.333	536.45	71.111
1:24000	2,000.00	0.500	2.400	0.379	609.60	91.827
1:25000	2,083.33	0.480	2.534	0.305	635.00	99.639
1:31680	2,640.00	0.379	2.000	0.500	804.67	160.000
1:48000	4,000.00	0.250	1.320	0.758	1,219.20	367.309
1,62500	5,208.33	0.192	1.014	0.986	1,587.50	622.744
1:63360	5,280.00	0.189	1.000	1.000	1,609.35	640.000
1:100000	8,333.33	0.120	0.634	1.578	2,540.00	1,594.225
1:125000	10,416.67	0.096	0.507	1.973	3,175.01	2,490.980
1:126720	10,560.00	0.095	0.500	2.000	3,218.69	2,560.000
1:250000	20,833.33	0.048	0.253	3.946	6,350.01	9,963.907
1:253440	21,120.00	0.047	0.250	4.000	6,437.39	10,244.202
1:500000	41,666.67	0.024	0.127	7.891	12,700.02	39,855.627
1:750000	62,500.00	0.016	0.084	11.837	19,050.04	89,675.161
1:1000000	83,333.33	0.012	0.012	15.783	25,400.05	159,422.507
Formula	Scale / 12	12,000 / Scale	63,360 / Scale	Scale / 63,360	Feet per Inch X 0.3046	(Scale)2 / 43,560X144

Source: Hunt (1984)

Table 2.1-1

A Guide to Map Scales

Imagery	Procurement platform	Image scale	Image form	Availability	Source
Multispectral scanner (MSS)*	Unmanned satelite (ERTS-1, LANDSAT)	1:1,000,000-1:250,000 (resolution 80 m)	B&W negative or print of electronic image in four wavelength ranges (can be color-enhanced): band 4 (green), 0.5-0.6 μm; band 5 (red), 0.6-0.7 μm; band 6 (near IR), 0.7-0.8 μm; band 7 (near IR), 0.8 1.1 μm	Worldwide coverage every 18 days since July 1972.	EROS Data Center**
Multispectral cameral (S190A)	Manned spacecraft (SKYLAB)	1:1,000,000-1:250,000 (resolution 30-50 m)	Negatives and prints from six film and filter combinations: B&W IR (two wavelengths), color IR, high-resolution color, B&W (two wavelengths)	Limited worldwide coverage.	EROS Data Center
Earth terrain camera (S190B)	Manned spacecraft (SKYLAB)	1:905,000-1:125,000 (resoution 20-30 m)	Photographs with four film and filter combinations: IR color high-resolution color, high definition B&W high-resolution IR color	Limited worldwide coverage.	EROS Data Center
Side-looking airborne radar (SLAR)	Aircraft	1:300,000, 1:125,000, 1:30,000 (occasional)	B&W print of electronic image (wavelengths 1 mm-4m)	Very limited coverage. Procurement costly.	Private companies
Thermal IR Scanner	Aircraft	Varies with platform altitude	B&W or color enhanced prints† of electronic image; wavelengths 8-14 μm	Very limited coverage. Procurement relatively costly.	Private companies
Aerial cameras	High-altitude aircraft (U-2, RB-57)	1:125,000, 1:100,000	B&W or color stereo pairs of aerial photos of high resolution	Limited worldwide coverage.	EROS Data Center
Aerial cameras	Moderate- to low-altitude aircraft	Varies with altitude; usually 1:60,000-1:8,000	(a) B&W or color stereo pairs of aerial photos of high resolution; (b) B&W or color IR	(a) U.S. complete coverage; (b) worldwide coverage, extensive.	Private companies, government agencies‡
Multispectral cameras	Moderate- to low-altitude aircraft	Varies with platform altitude	Negatives and photos from various film and color combinations; prints or projections color-enhanced† for interpretation	Very limited coverage.	Private companies
Side-scan sonar	Water vessels	Large scales	B&W print of electronic image	Very limited coverage.	Private companies

* Stereosat with resoluation of 15 m and image pairs suitable for stereoscopic viewing and production of topographic maps at 1:100,000 may be available by 1984 [Godfrey (1979)[a]
† Color-enhancement obtained by projection of various wavelengths through filters and combining the results (false-color imagery).
‡ Photos normally used for photogrammetric mapping.
** EROS Data Center, USGS Sioux Falls, S.D. 57198
NOTE: B&W-black and white, IR-infrared.

Table 2.1-2

Source: Hunt (1984)

Forms of Remote-sensing Imagery

Information desired	Applicable imagery
Regional geologic mapping and delineation of major structural features (*a*) Global coverage, moderate resolution (*b*) High resolution, but incomplete global coverage (*c*) Useful for areas of perennial cloud cover and heavy vegetation; low resolution	Space platform and SLAR: (*a*) ERTS and LANDSAT (MSS) (*b*) Multispectral camera (SKYLAB), earth terrain camera (SKYLAB) (*c*) Side-looking airborne radar (SLAR)
Detailed mapping of rock type, structure, soil formations, drainage, groundwater, slope failures, sinkholes, etc.: (*a*) Moderately large areas (*b*) Large areas, general mapping (*c*) Small areas, detailed mapping	Stereo pairs of aerial photos (preferably B&W): (*a*) Scale 1:100,000 (*b*) Scale 1:60,000–1:40,000 (*c*) Scale 1:20,000–1:8,000
Improved definition of surface and groundwater conditions on large- to local-area basis, such as land-water interface, seepage, ground moisture (important for sinkhole and fault identification)	B&W or color IR photos, preferably in stereo pairs
Seafloor and other underwater conditions (rock outcrops, soils, sunken vessels, pipelines, etc.)	Side-scan sonar

NOTES: Normal studies of large land areas, such as for highways, airports, industrial zones, new communities should be based on the interpretation of aerial photos of at least two scale ranges (1:60,000–1:40,000 and 1:20,000–1:8,000).

Studies of areas where seismicity is of concern should always begin with interpretations of ERTS/LANDSAT imagery, then be supplemented by interpretation of normal study imagery scales.

Information desired	Applicable imagery
Regional environmental studies of air, water and vegetation quality, flooding: (*a*) On a changing or seasonal basis (*b*) High resolution but incomplete global coverage	Satellite and space platforms: (*a*) ERTS and LANDSAT (MSS) (*b*) SKYLAB
Surface and groundwater studies (large to local areas): (*a*) General (*b*) Thermal gradients indicative of pollution or saltwater intrusion of surface waters (*c*) Subsurface seepage	IR and multispectral imagery: (*a*) B&W or color IR photos, multispectral photos (*b*) Thermal IR scanner (*c*) Thermal scanner
Vegetation: Forestry and crop studies (large to local areas); identify types, differentiate healthy from diseased vegetation	B&W or color IR, multispectral photos
Mineral resource studies: (*a*) Based on landform analysis (*b*) Based on plant indicators	Various types: (*a*) ERTS, LANDSAT, SKYLAB, aerial photos (*b*) Multispectral photos

Source: Hunt (1984)

Table 2.1-3

Uses of Remote-sensing for Engineering Geologic Mapping and Environmental and Natural Resource Studies

GENERAL PROCUREMENT OF PUBLICATIONS FROM THE U.S. GEOLOGICAL SURVEY, U.S. DEPARTMENT OF THE INTERIOR

Source	Publications
U.S. Geological Survey Circular 900, "Guide to Obtaining USGS Information" Free upon reqest from: Open File Reports Section U.S. Geological Survey Federal Center, Box 25425 Denver, Colorado 80225 (303) 236-7476	
Public Inquiries Offices (PIOs)	Professional papers, bulletins, and water-supply papers sold over the counter.
Distribution Offices (USGS)	Catalogs and lists of publications Lists by state of geologic and water-supply reports and maps Circulars and open-file reports Geologic quadrangle maps (GQ)
Regional basis--PIOs	Geophysical Investigaions Maps (GP) (aeromagnetic) Hydrological Investigaions Atlases (HA) Water Resources Investigaiton Reports (WRI) Geologic Map Indexes by state Topographic maps including orthophoto maps River survey maps
EROS Data Center, USGS Sioux Falls, SD 57198	ERTS and LANDSAT Imagery USGS aerial photography NASA aircraft data
Regional Engineering Offices	Aerial photographs

Table 2.1-4

Sources of Publications from the USGS

Source: Hunt (1984)

PROCUREMENT OF REMOTE-SENSING IMAGERY

(A) ERTS-1, LANDSAT, SKYLAB, HIGH-ALTITUDE NASA STEREO PHOTOS

EOSAT LANDSAT CUSTOMER SERVICE
EROS Data Center, USGS
Sioux Falls, SD 57198
(605) 594-2291

(B) LANDSAT FROM FOREIGN COUNTRIES

Integrated Satellite Information
Box 1630
Prince Albert, Saskatchewan S6U 5T2
Canada

Instituto de Pesquisas Especiais (INPE
Attn. Devisao de Banco de Dados
Av. dos Astronautal 1758
Caixa Postal 515
12.200 Sao Jose dos Campos,SP
Brazil

Department of Forestry and Agriculture
Building 810
Pleasantville
St. Johns, Newfoundland A1A 1P9
Canada

Telespazio--SES
Corso D'Italia
L-3 Roma
Italy

(C) AERIAL PHOTOGRAPHS (GENERALLY AT 1:20,000) OF THE UNITED STATES AND POSSESSIONS

1. USGS: National Cartographic Information Center (NCIC) provides catalogs.
   U.S. Geological Survey
   EROS Data Center
   Sioux Falls, SD
   57198

2. SCS provides a catalog, "Status of Aerial Photography"
   Soil Conservation Service
   Cartographic Devision
   6505 Belcrest Road
   Hyattsville, MD 20782
   (301) 436-8756

3. Agricultural Stabilization Conservation Service (ASCS)
   Aerial Photography Division
   ASCS-USDA
   2505 Parley's Way
   Salt Lake City,UT 84109
   (801) 524-5856

Source: Hunt (1984)

Table 2.1-5

Procurement of Remote-sensing Imagery

INFORMATION SOURCES: U.S. GEOLOGICAL SURVEY AND OTHERS

U.S. GEOLOGICAL SURVEY

USGS Water Resources Division
New England District
10 Causeway Street Suite 926
Boston, MA 02222-1040
(617) 565-6860

Hydrologic Information Unit
U.S. Geological Survey
419 National Center
Reston, VA 22092
(703) 648-6817

National Water Data Exchange
U.S. Geological Survey
421 National Center
Reston, VA 22092
(703) 648-5677

Water Resources Scientific Information Center
U.S. Geological Survey
425 National Center
Reston, VA 22092
(703) 648-6821

National Earthquake Information Center
U.S. Geological Survey
Mail Stop 967
Box 25046, Federal Center
Denver, CO 80225
(303) 236-1500

Geologic Inquiries Group
U.S. Geologic Survey
907 National Center
Reston, VA 22092
(703) 648-4383

National Cartographic Information Center
U.S. Geological Survey
507 National Center
Room 1-c-107
12201 Sunrise Valley Drive
Reston, VA 22092
(703) 860-6045

Books and Open File Reports
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225
(303) 236-7476

Map Distribution Section
U.S. Geological Survey
Federal Center, Box 25286
Denver, CO 80225
(303) 236-7477

NATIONAL TECHNICAL INFORMATION SERVICE (NTIS)

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22151
(703) 487-4650

SUPERINTENDENT OF DOCUMENTS

U.S. Government Printing Office
Washington, D.C. 20402

REGIONAL ENGINEERING OFFICES (USGS)

Atlantic Region Engineering
U.S. Geological Survey
1109 N. Highland Street
Arlington, VA 22210

Rocky Mountain Region Engineer
U.S. GeologicalSurvey
Building 25, Federal Center
Denver, CO 80225

Central Region Engineer
U.S. Geological Survey
Box 133
Rolla, MO 65401

Pacific Region Engineer
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 940 25

CARTOGRAPHIC DIVISION
SOIL CONSERVATION SERIVCE

Federal Center Building
Hyattsville,MD 20782

NATIONAL OCEAN SURVEY

Department of Commerce
Washington Science Center
Rockville, MD 20852

Source: Hunt (1984)

Table 2.1-6

General Sources of Information: USGS and Others

State Geoscience Agencies (SGA)

Many State geoscience agencies sell USGS products (book reports, maps, etc.) that pertain to their regions or States. Some State geoscience agencies are also affiliated with the National Cartographic Information Center (see NCIC entry). The USGS cooperates with State geoscience agencies in a variety of projects; publications resulting from these projects are commonly available from both organizations.

In addition to selling USGS products, many State geoscience agencies maintain reference collections that include USGS materials. State geoscience agencies allow the public to consult, but not borrow, these materials. Certain State geoscience agencies are also designated as depositories of specific USGS Open-File Reports.

Alabama
Geological Survey of Alabama
Attn: Ernest A. Mancini
Drawer 0
University Station
Tuscaloosa, AL 35486-9780
Phone: (205) 349-2852
Fax: (205) 349-2852 ext. 294

Alaska
Alaska Division of Geological and Geophysical Surveys
Attn: Robert B. Forbes
3700 Airport Way
Fairbanks, AK 99709-4699
Phone: (907) 451-2760
Fax: (907) 451-2703

Arizona
Arizona Geological Survey
Attn: Larry D. Fellows
Suite 100
845 N. Park Ave.
Tuscon, AZ 85719
Phone: (602) 882-4795

Arkansas
Arkansas Geological Commission
Attn: Norman F. Williams
Vardelle Parham Geology Center
3815 W. Roosevelt Rd.
Little Rock, AR 72204
Phone: (501) 371-1488

California
California Department of Conservation
Division of Mines and Geology
Attn: Joseph I. Ziony
Room 1341
1416 Ninth St.
Sacramento, CA 95814
Phone: (916) 445-1923
Fax: (916) 445-5718

Colorado
Colorado Geological Survey
Attn: John Rold
Room 715
1313 Sherman St.
Denver, CO 80203
Phone: (303) 866-2611
Fax: (303) 866-2115

Connecticut
Connecticut Geological and Natural History Survey
Attn: Richard Hyde
Room 553
State Office Building
165 Capitol Ave.
Hartford, CT 06106
Phone: (203) 566-3540

Delaware
Delaware Geological Survey
Attn: Robert R. Jordan
DGS Building
University of Delaware
Newark, DE 19716
Pone: (302) 451-2833
Fax: (302) 292-3579

Florida
Florida Geological Survey
Attn: Walt Schmidt
903 W. Tennessee St.
Tallahassee, FL 32304-7795
Phone: (904) 488-4298
Fax: (904) 488-8086

Georgia
Georgia Geologic Survey
Department of Natural Resources
Room 400
19 Martin Luther King Jr. Dr. SW
Atlanta, GA 30334
Phone: (404) 656-3214

Hawaii
Hawaii Department of Land and Natural Resources
Attn: Manabu Tagomori
Division of Water and Resource Management
Box 373
Honolulu, HI 96809
Phone: (808) 548-7533
Fax: (808) 548-6052

Idaho
Idaho Geological Survey
Attn: Earl H. Bennett
Room 332
Morrill Hall
University of Idaho
Moscow, ID 83843
Phone: (208) 885-7991
Fax: (208) 885-5826

Source: Geotimes, 1990

Table 2.1-7

Sources of Geologic Information, State Agencies

Illinois
Illinois Geological Survey
Attn: M.W. Leighton
Natural Resources Building
615 E. Peabody Drive
Champaign, IL 61820
Phone: (217) 333-4747
Fax: (217) 244-7004

Indiana
Indiana Geological Survey
Attn: Norman C. Hester
611 N. Walnut Grove
Bloomington, IN 47405
Phone: (812) 855-9350
Fax: (812) 855-7899

Iowa
Iowa Department of Natural Resources
Geological Survey Bureau
123 N. Capital St.
Iowa City, IA 52242
Phone: (319) 335-1575
Fax: (319) 335-2754

Kansas
Kansas Geological Survey
1930 Constant Ave.
West Campus
University of Kansas
Lawrence, KS 66047
Phone: (913) 864-3965

Kentucky
Kentucky Geological Survey
Attn: Donald C. Haney
228 Mining and Mineral Resources Building
University of Kentucky
Lexington, KY 40506-0107
Phone: (606) 257-5500

Louisiana
Louisiana Geological Survey
Attn: John E. Johnston
Box G, University Station
Baton Rouge, LA 70893
Phone (504) 388-5320
Fax: (504) 388-5328

Maine
Maine Geological Survey
Attn: Walter A. Anderson
Department of Conservation
State House Station 22
Augusta, ME 04333
Phone: (207) 289-2801
Fax: (207) 289-2353

Maryland
Maryland Geological Survey
Attn: Kenneth N. Weaver
2300 Saint Paul St.
Baltimore, MD 21218
Phone: (301) 554-5559

Massachusetts
Massachusetts Office of Environmental Affairs
Attn: John P. DeVillars
20th Floor, Room 2000
100 Cambridge St.
Boston, MA 02202
Phone: (617) 727-9800
Fax: (617) 727-2754

Michigan
Michigan Geological Survey Division
Attn: Robert Reed
Box 30028
Lansing, MI 48909
Phone: (517) 334-6907
Fax: (517) 334-6919

Minnesota
Minnesota Geological Survey
2642 University Ave..
St. Paul, MN 55114-1057
Phone: (612) 627-4780
Fax: (612) 624-6369

Mississippi
Mississippi Bureau of Geology
Attn: S. Cragin Knox
Box 5348
Jackson, MS 39296-5348
Phone: (601) 354-5348
Fax: (601) 354-6327

Missouri
Missouri Department of Natural Resources
Division of Geology and Land Survey
Box 250
111 Fairgrounds Rd.
Rolla, MO 65401

Montana
Montana Bureau of Mines and Geology
Montana College of Mineral Science and Technology
Butte, MT 59701
Phone: (406) 496-4180

Nebraska
Nebraska Conservation and Survey Division
Attn: Perry B. Wigley
University of Nebraska
113 Nebraska Hall
Lincoln, NE 68588-0517
Phone: (402) 472-3471
Fax: (402) 472-2410

Nevada
Nevada Bureau of Mines and Geology
Attn: Jonathan G. Price
University of Nevada
Reno, NV 89557-0088
Phone: (702) 784-6691
Fax: (702) 784-1709

New Hampshire
New Hampshire Geological Survey
Attn: Eugene L. Boudette
New Hampshire Department of Environmental Services
117 James Hall
University of New Hampshire
Durham, NH 03824
Phone: (603) 862-3160
Fax: (603) 862-2030

New Jersey
New Jersey Geological Survey
Attn: Haig F. Kasabach
CN-029
Trenton, NJ 08625
Phone: (609) 292-1185
Fax: (609) 633-1004

New Mexico
New Mexico Bureau of Mines and Mineral Resources
Attn: Frank E. Kottlowski
Campus Station
Socorro, NM 87801
Phone: (505) 835-5420
Fax: (505) 835-6329

New York
New York State Geological Survey
Attn: Robert H. Fakundiny
3136 Cultural Education Center
Empire State Plaza
Albany, NY 12230
Phone: (518) 474-5816

Source: Geotimes, 1990

Table 2.1-7 (continued)
Sources of Geologic Information, State Agencies

North Carolina
North Carolina Geological Survey
Attn: Jeffrey C. Reid
Environment, Health and Natural Resources
Box 27687
Raleigh, NC 27611
Phone: (919) 733-2423
Fax: (919) 733-2622

North Dakota
North Dakota Geological Survey
600 East Blvd.
Bismarck, ND 58505
Phone (710) 224-4109

Ohio
Ohio Department of Natural Resources
Attn: Thomas M. Berg
Division of Geological Survey
4383 Fountain Square Drive
Columbus, OH 43224
Phone: (614) 265-6576
Fax: (614) 447-1918

Oklahoma
Oklahoma Geological Survey
Attn: Charles Mankin
Room N-131
Energy Center
100 E. Boyd
Norman, OK 73019-0628
Phone: (405) 325-3031
Fax: (405) 325-3180

Oregon
Oregon Department of Geology and Mineral Industries
Attn: Donald A. Hull
910 State Office Building
1400 SW 5th Ave.
Portland, OR 97201-5528
Phone: (503) 229-5580
Fax: (503) 229-5639

Pennsylvania
Pennsylvania Bureau of Topographic and Geologic Survey
Attn: Donald M. Hoskins
Department of Environmental Resources
Box 2357
Harrisburg, PA 17105
Phone: (717) 787-2169
Fax: (717) 772-2291

Puerto Rico
Puerto Rico Geological Survey Division
Attn: Ramon M. Alonso
Department of Natural Resources
Box 5887 Puerta de Tierra Station
San Juan, PR 00906
Phone: (809) 724-8774

Rhode Island
Rhode Island State Geologist
Attn: J. Allan Dain
Department of Geology
University of Rhode Island
Kingston, RI 02881
Phone: (401) 792-2265

South Carolina
South Carolina Geological Survey
Attn: Norman K. Olson
5 Geology Road
Columbia, SC 29210-9998
Phone: (803) 737-9440
Fax: (803) 737-9487

South Dakota
South Dakota Geological Survey
Science Center
University of South Dakota
Vermillion, SD 57069-2390
Phone: (605) 677-5227

Tennessee
Tennessee Division of Geology
Attn: William T. Hill
Suite B30
Customs House
701 Broadway
Nashville, TN 37243-0445
Phone: (615) 742-6689
Fax: (615) 742-6594

Texas
Texas Bureau of Economic Geology
Attn: W.L. Fisher
University of Texas
Box X, University Station
Austin, TX 7813-7508
Phone: (512) 471-1534
Fax: (512) 471-0140

Utah
Utah Geological and Mineral Survey
606 Black Hawk Way
Salt Lake City, UT 84108-1280
Phone (801) 581-6831
Fax: (801) 581-4450

Vermont
Vermont Geological Survey
Attn: Charles Ratte
Office of the State Geologist
103 South Main St.
Center Building
Waterbury, VT 05676
Phone: (802) 244-5164
Fax: (802) 244-1102

Virginia
Virginia Division of Mineral Resources
Box 3667
Charlottesville, VA 22903
Phone: (804) 293-5121
Fax: (804) 293-2239

Washington
Washington Department of Natural Resources
Attn: Raymond Lasmanis
Division of Geology and Earth Resources
PY 12
Olympia, WA 98504
Phone: (206) 459-6372
Fax: (206) 459-6380

West Virginia
West Virginia Geological and Economic Survey
Mont Chateau Research Center
Box 879
Morgantown, WV 26507-0879
Phone; (304) 594-2331

Wisconsin
Wisconsin Geological and Natural History Survey
3817 Mineral Point Road
Madison, WI 53705
Phone: (608) 262-1705
Fax: (608) 262-8086

Wyoming
Wyoming Geological Survey
Attn: Gary B. Galss
Box 3008
University Station
Laramie, WY 82071
Phone: (307) 766-2286

Source: Geotimes, 1990

Table 2.1-7 (continued)
Sources of Geologic Information, State Agencies

APPENDIX A

SITE ASSESSMENT CHECKLIST FOR USE DURING A SITE RECONNAISSANCE VISIT

SITE ASSESSMENT CHECKLIST
FOR USE DURING A SITE RECONNAISSANCE VISIT

Job No.__________________
Site Name________________
Client___________________
Date_____________________
Completed by_____________

MANMADE AND RELATED FEATURES

1. Buildings
   - Number, location, size ____________________________________
   - Type of construction ____________________________________
   - Age ____
   - General Condition ____________________________________
   - Flooring Materials ____________________________________
   - Floor drains; to where? ____________________________________
   - Spill evidence; cleaned up? ____________________________________

2. Utilities
   - Electricity ____________________________________
   - Natural Gas ____________________________________
   - Oil ____________________________________
   - Telephone ____________________________________
   - Sewers ____________________________________
   - Water ____________________________________
   - Storm drains ____________________________________

3. Physical Features
   - Parking areas (paved or under roof?) ____________________________________
   - Roads ____________________________________
   - Power lines ____________________________________
   - Dwellings ____________________________________
   - Structures/improvements ____________________________________
   - Rights-of-way ____________________________________

4. Security Features
   - Access roads ____________________________________
   - Fencing and gates ____________________________________
   - Vegetation barriers ____________________________________
   - Bike trails ____________________________________
   - Camp fire/party remains ____________________________________
   - Boat launching areas ____________________________________

5. Adjacent Land Use (Past and Present)
   - Surface water/groundwater use ____________________________________
   - Roads/utilities ____________________________________
   - Residential/industrial/commercial/agricultural ____________________________________

SITE ASSESSMENT CHECKLIST
FOR USE DURING A SITE RECONNAISSANCE VISIT

Job No.__________________
Site Name________________
Client ____________________
Date _____________________
Completed by______________
Page 2 of 4

Vacant land ____
Vegetation types ____________________________________
Drainage patterns____________________________________

NATURAL FEATURES

1. Vegetation Features and Condition
Type ____
Maturity____
Density____
Condition (stressed)_________________________________

2. Water Features
Wells ____
Springs/seeps _____________________________________
Wetlands (swamps, meadows, bogs) ________________________
Ponds/lakes ______________________________________
Streams ____
Direction of runon and runoff ___________________________
Surface erosion_ ___________________________________
Evidence of flooding_________________________________
Water body use ___________________________________

3. Geologic Features
Topography and slope _______________________________
Soil characteristics ________________________________
Rock outcrops ____________________________________
Sinkholes _______________________________________
Excavations _____________________________________
Spoil piles_______________________________________
Mining activity_____________________________________
Quarries or pits____________________________________
Diversion ditches __________________________________
Soil stockpiles ___________________________________
Aquifer characteristics ______________________________
Erosion____
Boulders____

SITE ASSESSMENT CHECKLIST
FOR USE DURING A SITE RECONNAISSANCE VISIT

Job No.________________
Site Name_______________
Client__________________
Date___________________
Completed by____________
Page 3 of 4

POTENTIALLY HAZARDOUS FEATURES

1. Waste Evidence

Drums, barrels, containers ____________________
Waste materials ____________________
Construction/demolition debris ____________________
Discolored soil ____________________
Odors ____________________
Leachate seeps ____________________
Discolored surface water ____________________
"Unnatural soil" ____________________
Ash or blackened area ____________________

2. Chemical/Fuel/Drum/Storage Area

Materials stored ____________________
Type of construction ____________________
Age ____________________
General condition ____________________
Security and access ____________________
Spill control berms ____________________
Spill evidence ____________________

3. Manholes/Catch Basins/Drains/Fill Pipes

Where ____________________
What for ____________________
Description ____________________
Unusual appearance or odors ____________________

4. Process Tanks/Wastewater Tanks

Size ____________________
Materials of construction ____________________
Purpose ____________________
Inside/outside appearance ____________________
Above/below grade ____________________
Lined/unlined ____________________
Contents ____________________
General condition ____________________
Leaks/spills-evidence or incidents ____________________
Connecting piping secure? ____________________
Chemical feed/pump system ok? ____________________

SITE ASSESSMENT CHECKLIST
FOR USE DURING A SITE RECONNAISSANCE VISIT

Job No._________________
Site Name_______________
Client__________________
Date____________________
Completed by____________

5. Pits/Ponds/Lagoons

Size/location ____
Materials and construction ____
Purpose/contents ____
Above/below ____
Lined/unlined____
General condition ____
Freeboard ____
Leaks____
Fill/drainpipes ____

6. Disposal Areas

Size ____
Location____
Age
Contents ____
General condition ____
Debris ____
Drums ____
Sludge/residue/rubble ____
Discoloration ____
Odors____
Monitoring wells____
Cover material____
Vegetation____
Equipment condition ____
Surface contours ____
Erosion ____
Leachate (analytical results) ____

7. Chemical Transfer Points

Where, when____
What chemicals____
Inside/outside)____
Paved/unpaved ____
Spill evidence ____

APPENDIX B

SITE RECONNAISSANCE FIELD SUMMARY

Job No.________________
Site Name______________
Client_________________
Date__________________
Completed by___________
Page 1 of 3

SITE RECONNAISSANCE FIELD SUMMARY

1. GENERAL
   Client ____
   Name of project ____
   Location of sit ____
   USGS Quadrangle_____________________Size of site _______________________
   Description of proposed development ______________________________________

   Available site plans and other drawings (Dwg. No., Title, Author, Date) (if no plans are available, prepare sketch and attach to report)

   Available photographs ____
   Available bedrock or surficial geology maps ___________________________________

2. SITE ACCESS
   Sketch location of roads and trails not shown on site plan and note type and condition. Describe type of exploration equipment which can be moved into site, e.g., small or large backhoe, either rubber-tired or tracked, truck mounted or skid-mounted drill rigs, small portable rigs, water availability for drilling, overhead utility restrictions, etc.
   ____
   ____

3. TOPOGRAPHY (Level - Rolling - Hilly - Mountainous, etc.)
   Describe ____

   Degree of slopes, approx. ____
   Max. elevation___________________Min. elevation ___________________________
   Reference datum (USGS MLS, Boston City Base, etc.) _______________________

4. GEOMORPHOLOGY
   (Tidal marsh - Drumlin - Flood Plain - Valley Floor, etc.)
   Describe ____

   ___________________________Is the site virgin?__________________________
   Character of erosion gullies (steep, moderate, or gently inclined)
   ____

SITE RECONNAISSANCE FIELD SUMMARY

Job No.________________
Site Name______________
Client_________________
Date___________________
Completed by___________
Page 2 of 3

5. SURFACE VEGETATION (Wooded - Brush - Grass - Cleared - Fill, etc.)
   Describe ____

   Size and type trees____

6. DRAINAGE (Locate features on sketch)
   Natural Streams and Springs (Estimate gradient and discharge)

   Man-made Drainage ditches and Culverts (describe type and estimate size, lined or unlined, headwalls, presence of water) ____________________________________
   ____

   Probable groundwater elevation (from observations in pits, wells)

   Evidence on history of flooding ____
   Max. flood el. ____

7. EXISTING STRUCTURES ON SITE OR NEARBY
   (Describe and locate on sketch)
   Buildings (Type, size owner, foundation, available borings) ____________________

8. SOIL AND ROCK FEATURES (Show applicable information on sketch)
   Bedrock Type Rock (outcrops, cuts) ___________________________________
   ____
   Joining and Fissility (Degree and angle)_______________________________
   Surface boulders (Size, number, type rock) ____________________________
   Stone walls (None, few, many) _______________________________________

   Soil Exposures (Describe types of materials and vertical sequence noted in each exposure, e.g. in open pits, roadway cuts, trenches, erosion gullies, etc.

   Artificial Fill (Granular, rubbish, cinders, etc.)_______________________________

SITE RECONNAISSANCE FIELD SUMMARY

Job No. _______________
Site Name______________
Client__________________
Date___________________
Completed by___________
Page 3 of 3

Topsoil Thickness and Type____
Organic Materials (Peat depths, limits, etc.)__________________________________

Probable Subsoil Conditions (Describe as completely as possible)

Previous Subsurface Explorations ____

9. SOURCES OF BORROW (Where applicable, give name and location of pit, name, address and telephone of owner, distance from site, type of soil, sample taken, price, estimated resources, etc.)

10. ADDITIONAL INVESTIGATIONS (If applicable to investigation, check public works department and town engineer for location of sewer lines, water lines, buried cables, septic tanks, etc. Include name and telephone numbers of people contacted)

11. ADDITIONAL COMMENTS AND NOTES

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 2.2   WORK AND COST PLANS (RESERVED)

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 2.3 HEALTH AND SAFETY PLANS

SECTION 2.3
HEALTH AND SAFETY PLANS

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SECTION 2.3
HEALTH AND SAFETY PLANS

2.3-1 PURPOSE

Workers at hazardous waste sites may be exposed to a variety of known and unknown physical and chemical hazards. To control worker exposure to these hazards, the Occupational Health and Safety Administration (OSHA), as required by Congress in the Superfund Amendments and Reauthorization Act (SARA) of 1986, developed the Hazardous Waste Operations and Emergency Response standard-interim final rule, 29 CFR 1910.120, to regulate employee safety and health at hazardous waste operations. One portion of this standard addresses site-specific Health and Safety Plans (HASPs). The purpose of this Standard Reference is to present guidelines and a methodology for developing HASPs. A site-specific HASP is necessary to address the health and safety hazards anticipated at a particular site, and to describe the means that will be used to eliminate or control hazardous exposure in order to reduce the risk of bodily injury. The HASP must be developed in a systematic manner so that all hazards and necessary protective actions are addressed. A well developed HASP should provide all the information needed for site personnel to work in safety, and respond to emergencies in a quick, safe, and efficient manner.

The Health and Safety Plan guidelines outlined in these Standard References pertain to hazardous waste sites and any emergency response actions that may occur at a site. Specific guidelines for emergency response actions at uncontrolled releases of oil or hazardous materials may differ.

2.3-2 APPLICABILITY

All hazardous waste sites covered by 29 CFR 1910.120 are required to develop site-specific HASPs. In Sections (a)(1) and (2) of the Hazardous Waste Operations and Emergency Response rule, the scope of coverage is described. To summarize this section, employers and employees engaged in the following operations are required to comply with the regulation:

- Operations involving hazardous substances that are conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980

- Clean-up operations involving major corrective actions conducted under the Resource Conservation and Recovery Act (RCRA) of 1976

- Operations at hazardous waste sites that have been designated for cleanup by state or local governmental authorities

- Operations at treatment, storage, and disposal (TSD) facilities involving hazardous wastes regulated under 40 CFR Parts 264 and 265, pursuant to RCRA

- o Emergency response operations for release of, or substantial threats of, hazardous substances without regard to the location of the hazard

2.3-3 REQUIREMENTS

The Hazardous Waste Site and Emergency Response rule (29 CFR 1910.120) also specifies certain items that must be addressed in the HASP. (See Appendix A.) In addition to pertinent site information, all HASPs, at a minimum, must contain the following information, although the level of detail provided should be dependent upon the anticipated risk and exposure:

- o Personnel:

Key health and safety personnel are those who either have health and safety responsibilities on-site or are utilized as a backup if an emergency occurs. These personnel include: (1) at the corporate level, the Health and Safety Manager (HSM), who is responsible for implementing all health and safety programs within the corporation; (2) at lower corporate levels, the Health and Safety Supervisor (HSS) and the Health and Safety Officer (HSO), who are responsible for designing site-specific HASPs and auditing compliance with the HASP; (3) at a site level, the Health and Safety Designee (HSD), if one is so designated, who assists the HSO when multiple operations are conducted that require air monitoring; (4) the Industrial Hygienist; and (5) other relevant individuals.

- o Risk or Hazard Analysis:

The purpose of the risk or hazard analysis is to determine the extent of worker exposure during the conduct of various operations at the site. The analysis is conducted by reviewing all available data on the potential hazards at the site, both chemical and physical. It is necessary to determine the potential for worker exposure, based on the levels and types of contaminants known or suspected to be on-site, as well as the site conditions and the work to be done. The analysis must include an evaluation of the potential risks or hazards from accidents or major catastrophes.

- o Training Requirements:

All site personnel who may potentially be exposed to hazardous materials at a hazardous waste site See Table 2.3-1. Site personnel must also receive eight hours of refresher training each year. On-site management and supervisors directly responsible for employees engaged in hazardous waste operations must receive an additional eight hours of supervisory training.

- o Personal Protective Equipment (PPE):

Selection of the appropriate PPE is a complex process that must consider a variety of factors, including the identification of known or suspected hazards, their routes of entry into the body (i.e., skin absorption, inhalation, or ingestion), and the performances of the PPE. Before selecting PPE, engineering controls must be taken into account. If it is feasible to use engineering controls and work practices to limit or reduce the exposure, they must be given priority over the use of PPE. Types of engineering controls that may be feasible include the use of pressurized cabs or control booths on equipment, the use of remotely operated material handling equipment, wetting down soil to control dust, and ventilating a confined space.

- Medical Monitoring:

Any employees exposed or potentially exposed for 30 days or more per year to hazardous substances or health hazards, at levels that equal or exceed the exposure levels established by OSHA, the National Institute for Occupational Safety and Health (NIOSH), or the American Conference of Governmental Industrial Hygienists (ACGIH), or who wear respirators for 30 days or more a year, must be enrolled in a medical surveillance program.

- Monitoring:

The frequency and types of air monitoring, personnel monitoring, and environmental sampling techniques and instrumentation to be used should be described. The methods of maintenance and calibration of monitoring and sampling equipment to be used should also be included.

- Site Control Measures:

  Appropriate site control procedures must be implemented before work begins. To control employee exposure to hazardous substances, the site control program must include, at a minimum, a site map, site work zones (i.e., Exclusion Zone, Contamination Reduction Zone [CRZ], and Support Zone - see Figure 2.3-1), the use of a "buddy system," site communications, the standard operating procedures for safe work practices, and identification of the nearest medical assistance, including written directions and a map showing the most direct route to the facility.

- Decontamination:

A decontamination procedure must be developed, discussed with all on-site employees, and implemented before any work may be undertaken in areas on-site where a potential for exposure to hazardous substances exists.

- Emergency Response:

An emergency response plan must be developed to cover all anticipated emergencies prior to the commencement of work on-site.

- Confined Space Entry Procedures:

  If employees will be required to enter a confined space, entry procedures must be developed and communicated to the employees before the commencement of work. If entry into a confined space will not be required, a statement stating this must be included in the HASP.

The HASP should always be regarded as a dynamic document, subject to revision as more information becomes available or as site conditions change. The initial development, subsequent revisions, and implementation of the HASP are the responsibility of the HSO assigned to the site. When developing a HASP, the HSO will gather the necessary information about the site from past records, including what was disposed of; complaints from the public on odors, illnesses, or injuries that may be site related; any previous agency action (e.g., prior investigations, response to spills or leaks, fires, or response to complaints of contaminated water); worker or non-worker injury that may have occurred on-site while the site was in operation or when prior investigations were underway; and prior sampling episodes.

A preliminary HASP must then be developed to beused for the site reconnaissance. This important preliminary work step sets the framework for the execution of the remainder of the project HASP. It enables the HSO to develop a layout of the site, identify site hazards, establish the appropriate level of personal protection, verify information about the site, and provide additional information for use in other work-related matters (e.g., locating future monitoring wells and test pits).

All information gained is later incorporated into a site-specific HASP. As additional information relative to the site becomes available, or work conditions change, revisions to the HASP must be made. These changes must be communicated to all affected personnel.

2.3-4 PERSONAL PROTECTION LEVELS

Levels of personal protection were first developed by the U.S. Environmental Protection Agency (USEPA) and later adopted by OSHA in the Hazardous Waste Operations and Emergency Response rule. This section summarizes the protection levels appropriate for various conditions. Appendix B lists the OSHA-recommended equipment per level of protection.

2.3-4.1 Level A

Level A personal protection provides the highest level of protection for the skin, eyes, and respiratory system. It is appropriate for conditions where there are potential or actual high concentrations of atmospheric vapors, gases, or particulates. It should be used if site operations or work functions involve a high potential for splash, immersion, or exposure to unexpected vapors, gases, or particulates of materials that are harmful to the skin or capable of being absorbed through the intact skin. Level A is primarily used for emergency situations or when the following conditions exist: (1) vapors/mists of strong acids; (2) known or probable "Immediately Dangerous to Life and Health" (IDLH) atmospheres with dermally active compounds; (3) high atmospheric concentrations of compounds that can be absorbed through the skin; and (4) operations that must be conducted in a confined, poorly ventilated area, where conditions requiring Level A have not yet been eliminated. The key PPE in Level A personal protection are the fully encapsulating suit and the positive pressure/pressure demand self-contained breathing apparatus (SCBA) or hoseline respirators.

2.3-4.2 Level B

Level B personal protection should be used when the type and atmospheric concentration of substances have been identified and require a high level of respiratory protection; however, the atmospheric contaminant, splashing liquid, or other direct contact will not adversely affect or be absorbed through any exposed skin. This includes atmospheres with IDLH concentrations of specific substances that do not represent a severe skin hazard, or that do not meet the criteria for use of air purifying respirators. Level B has the same respiratory protection criteria as Level A, but the dermal exposure is not as severe. Level B is also required where cartridge-type respirators are not available for the contaminant of concern.

2.3-4.3 Level C

Level C personal protection should be used when the atmospheric contaminant, liquid splashes, or other direct contact will not adversely affect or be absorbed through any exposed skin. In addition, the types of air contaminants must have been identified, the concentration measured, and an air-purifying respirator made available that can remove the contaminants. Air-purifying respirators can only be used if the oxygen content in the air is at least 19.5 percent, the contaminant has adequate warning properties (e.g., odor, taste, and irritating effect thresholds within two to three times the Threshold Limit Values [TLVs]), the concentration of the contaminant does not exceed the IDLH, and the worker has been fit tested. Level C has the same splash protection as Level B, but cartridge respirators are used instead of SCBAs.

2.3-4.4 Level D

Level D personal protection requires a work uniform affording minimal protection; it is used only for nuisance contamination. This level of protection should only be used when the atmosphere contains no known hazard; all potential airborne contaminants can be monitored for; and work functions preclude splashes, immersion, or the potential for unexpected inhalation of or contact with hazardous levels of any chemical.

2.3-5 QUESTIONS AND SUGGESTED SOLUTIONS

This section presents some problems that may be encountered when developing a HASP and suggests possible methods for developing solutions.

PROBLEM: How to ensure that a preliminary HASP is developed prior to site reconnaissance.

DISCUSSION: Frequently, to get a project moving, preliminary site walk-overs occur without first taking the time to develop a preliminary HASP. A preliminary HASP is required by OSHA; it is the same as the regular HASP except it is based solely on information gathered off-site (e.g., from background checks, complaints from the public, previous agency action, and prior injuries or illnesses). This document should be as complete as possible, based on all the information available at the time. If the preliminary off-site assessment does not produce sufficient information to identify the hazards or suspected hazards at a site, OSHA requires that initial site entry be conducted in Level B PPE. Therefore, the preliminary HASP enables workers to conduct the initial reconnaissance in a safe manner, whether it be in Level B, C, or D PPE.

POSSIBLE SOLUTIONS: Training is important. Ensure that all personnel, from management down, know of the requirements and the reasons for the preliminary HASP. Establish a communication network between Project Managers and health and safety personnel to review the information found during the preliminary site evaluation and determine an adequate level of protection.

PROBLEM: How to determine the level of personal protection to be used on-site.

DISCUSSION: When determining the proper level of personal protection, the more information that is available about the site, the better. If in doubt, the level of protection selected should be conservative so as to protect the health of the workers. However, if a greater level of personal protection is selected than needed, problems inherent with the equipment could not only increase the cost of the project (due to the costs associated with the equipment and the reduction in work efficiency associated with wearing the equipment), but also make it more hazardous than the hazard itself.

For example:

Respirators

- reduce visibility
- affect communication
- increase breathing resistance
- are bulky and heavy (SCBAs)
- sometimes impair mobility (air-line)
- reduce endurance, especially in a hot environment

Chemical Protective Clothing

- cause heat stress, a very serious consideration; worker tolerance level can be reduced as much as 56 percent when working in a hot environment

Steel-toe, Steel-shank, Chemical-resistant Boots

- are hot in the summer (heat stress)
- are cold in the winter (frostbite)

Gloves

- reduce dexterity, especially if multiple pairs are used
- are hot in the summer (heat stress)

POSSIBLE SOLUTIONS: Conduct a hazard analysis, using all available information, and estimate the potential for exposure. The more information available, the better the evaluation. If no or very little information is available about the contaminants and the site, a higher level of protection must be selected. If data are available on the types, concentrations, and locations (aboveground or below ground) of contaminants, and the type of work to be done, a lower level of protection may be safely selected.

Once the level of PPE is chosen, the type of glove, boot, and chemical-resistant clothing can be selected. This selection is based on the contaminants found on-site and on how well the material resists degradation or permeation by the contaminant. See Appendix B for a table on the Effectiveness of Protective Materials Against Chemical Degradation (by Generic Class).

PROBLEM: How to go about conducting a risk or hazard analysis.

DISCUSSION: A risk or hazard analysis is required by OSHA when developing a HASP. The purpose of the risk/hazard analysis is to evaluate all the information available, identify the hazards, and develop controls.

POSSIBLE SOLUTION: When conducting a risk/hazard analysis, the more information available, the better the analysis. If available information is limited, a higher degree of hazard must be assumed until enough data are compiled to determine otherwise.

To conduct a chemical risk/hazard analysis, the first step is to identify the types of contaminants on-site. How hazardous are they? Are they in high enough concentration to pose a health hazard? What type of work is to be conducted? Where are the contaminants found? If found only in the groundwater, and the work is non-invasive, the risk of exposure may be low or nonexistent. If the contaminants are found at the surface and the concentrations are high, the risk of exposure may be high. What are the routes of entry into the body (i.e., inhalation, ingestion, skin absorption, or injection)? Evaluate the contaminant's physical properties. For example, is it a solid, liquid, or gas? If it is a solid, the exposure route will be primarily dermal, with some possibility of particulate inhalation. If the contaminant is a gas or a volatile liquid, inhalation is the route of most concern. What is the contaminant's vapor pressure? Vapor pressure is an indicator of the chemical's volatility. All this information should be analyzed to determine the risk of exposure.

When conducting risk/hazard analyses, care must be taken when determining which established exposure limit (EEL) to use. OSHA has developed permissible exposure limits (PELs), which are legally enforceable.

Neither the ACGIH TLVs nor the NIOSH Recommended Exposure Limits (RELs) are enforceable, because they are recommended limits only. However, the TLVs and RELs are based on current experimental and epidemiologic data and are updated regularly. Therefore, except when the OSHA PELs are lower, prudence recommends the use of TLVs or RELs when determining EELs. See Appendix D for calculations that can be used in the analysis.

Although chemical exposures are first in order of concern, physical hazards must also be evaluated. Physical hazards are represented by rough or uneven terrain, test pits, ditches, or inadequate stairs for the trailer. Such hazards may cause slips, trips, or falls. Improper materials handling may lead to back, shoulder, or arm strain; working around drilling rigs can cause injury due to the hammer, rods, augers, or similar equipment falling and striking personnel. Also, heat stress, cold stress, and noise exposure may occur. In addition to physical hazards, biological, radiological and electrical hazards must be evaluated.

<u>PROBLEM</u>: How to determine if there is a confined space exposure on-site.

<u>DISCUSSION</u>: Confined spaces can be categorized generally as areas where air circulation is minimal or restricted, and where the potential exists for concentration or stratification of gases. Test pits, trenches, ditches, depressions, diked areas around a tank, and certain types of storage tanks may be classified as open-top confined spaces. If the contaminant is heavier than air (i.e., butane, propane, and other hydrocarbons), it flows to the lowest point, where it is difficult to remove.

Other confined spaces (e.g., sewers, casings, tanks, basements, silos, vaults, and compartments of ships) usually have limited access. The problems arising in these areas are similar to those that occur in open-top confined spaces. However, the limited access increases the risk of injury. Gases that are heavier than air (e.g., carbon dioxide and propane) may lie in a tank or vault for hours, or even days, after the container is opened.

Gases that are lighter than air (e.g., hydrogen and methane) may also be trapped within an enclosed-type confined space, especially those with access from the bottom or side.

POSSIBLE SOLUTIONS: Ensure that personnel are trained in how to recognize a confined space. Monitoring equipment should be employed prior to entry into any confined or semi-confined area. Analyze the confined space for oxygen content. Analyze the contaminants suspected and known to be on-site. Determine which are heavier and lighter than air. When conducting the initial reconnaissance, instruct field personnel to be on the lookout for any low-lying terrain where heavier-than-air contaminants could be trapped during work activities. Be careful of any work done inside buildings, especially basements, which can be considered confined spaces if not well ventilated. Confined spaces should never be entered alone. A backup is always required.

PROBLEM: How to deal with the press, politicians, vandals, and others who want to enter an unauthorized zone.

DISCUSSION: OSHA regulations are very specific on the training and health monitoring requirement for hazardous waste sites. If on-site more than 30 days per year, personnel must have received all the required training and must be enrolled in a medical surveillance program.

POSSIBLE SOLUTION: To prevent unauthorized access and thereby exposure of unauthorized, unprotected people, plan to have and maintain good site security in the Support Zone and at the Access Control Points. Assign a person responsibility for enforcing authority for entry and exit requirements. Have the Project Team Leader approve all visitors to the site. If possible, erect a fence or other physical barrier around the site. If the site is not fenced, post signs around the perimeter and use guards to patrol. Enlist public enforcement agencies (e.g., the local police department) if needed. Have a public relations person assigned to deal with the press and politicians, as well as the public. Have this person assigned to the site or refer the press and politicians to the telephone number where this person can be reached.

PROBLEM: How to obtain local emergency numbers (e.g., for hospitals, police, fire department, and poison control) in the easiest possible way.

DISCUSSION: Emergency numbers as well as the route to the hospital are required as part of the emergency response plan.

POSSIBLE SOLUTIONS: When first in the area of the site, acquire a local telephone book from the telephone company and/or contact the local police and fire departments. Police and fire departments are a good source for emergency numbers, as well as getting the best route to the hospital. These sources should provide most of the information needed.

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SECTION 2.3 HEALTH AND SAFETY PLANS

APPENDICES

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C RISK/HAZARD ANALYSIS CALCULATIONS

APPENDIX A

EXAMPLE OF SITE-SPECIFIC HASP FORMAT

HEALTH AND SAFETY PLAN (HASP)

Prepared for:

(identify the site)

(identify city, county, and state)

Prepared by:

ABC ENGINEERING CO.
ANYTOWN, MASSACHUSETTS

(enter date as month and year prepared/revised)

(NOTE: Do not leave blanks in the HASP!
If sections are not considered necessary or
applicable, state this.)

The attached sample HASP contains all elements required by OSHA, but the format used is only one of many acceptable versions. DEP does not require use of a particular format; as long as the HASP conforms to OSHA and other applicable regulations, format is at the discretion of the preparer.

The sample HASP can and should be adapted as necessary to address site- and project-specific details and concerns. For example, when a HASP is submitted in conjunction with a work and cost plan, sections that are common to both (such as scope of work and site history) need not be repeated.

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EXAMPLE OF SITE-SPECIFIC HASP FORMAT

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APPENDIX A EXAMPLE OF SITE-SPECIFIC HASP FORMAT

A.1 GENERAL

A.1.1 Scope and Purpose

This Health and Safety Plan (HASP) was prepared in conform with the ABC Engineering Co. Health and Safety Program, and is intended to meet the requirements found in 29 CFR 1910.120. As such, the HASP addresses all activities associated with field operations at the (* identify the site). Compliance with this HASP is required of all ABC Engineering Co. personnel, contractor's personnel, or third parties entering the site.

A.1.2 Health and Safety Personnel

The following paragraphs briefly describe the health and safety designations and general responsibilities that will be employed for the (* identify the site) project. Other personnel without specific safety designations (e.g., the Project Manager, Field Operations Leader [FOL], and the field crew) should remember that safety is everyone's responsibility and should tailor their actions and decisions accordingly.

A.1.2.1 Health and Safety Manager

The Health and Safety Manager (HSM) for ABC Engineering Co., J.A. Smith, can be reached at (617) 123-4567, in Anytown, Massachusetts. The HSM has final authority to resolve health and safety issues that are not resolved at the site or through the Health and Safety Supervisor (HSS), and has overall responsibility for ensuring that the policies and procedures of this HASP are implemented by the Health and Safety Officer (HSO). In the various regions, the HSM may delegate additional functions to the Regional HSS.

A.1.2.2 Health and Safety Supervisor

The HSS for ABC Engineering Co., D.E. Jones, can be reached at (617) 123-4567, in Anytown, Massachusetts. The HSS is the health and safety professional serving as the ABC Engineering Co. HSM's designee for this project. As such, the HSS will be responsible for (1) approval of the individual chosen to serve as the site HSO for this field operation; (2) review and approval of site-specific HASPs developed by the HSO, as well as any significant changes made over time to the site HASP; (3) oversight of the daily efforts of the HSO; (4) resolution of site disputes involving health and safety issues; (5) implementation of the HASP by the HSO; and (6) conduct of health and safety audits at the site (see Attachment 2). The HSS will notify the HSM of any Stop Work Orders issued by an HSO.

A.1.2.3 Health and Safety Officer

(* Enter name of HSO) has been approved as the HSO for the (* identify the site) by the ABC Engineering Co. HSS. The HSO is responsible for developing and implementing this site-specific HASP in accordance with the ABC Engineering Co. Health and Safety

Program. The HSO will conduct safety inspections and investigate all accidents, illnesses, and incidents occurring on-site. The HSO will also conduct safety briefings and site-specific training for on-site personnel. As necessary, the HSO will accompany all U.S. Environmental Protection Agency (USEPA), Occupational Safety and Health Administration (OSHA), or other governmental agency personnel visiting the site in response to health and safety issues. The HSO, in consultation with the HSS, is responsible for updating and modifying this HASP as site or environmental conditions change.

The HSO is vested with the authority to stop site operations (STOP WORK AUTHORITY) if he/she determines that an imminent health or safety hazard or other potentially dangerous situation exists. The HSO is to immediately notify the HSS of any Stop Work Orders issued. The HSO may also recommend to the HSS or HSM that the downwind authorization of individual site personnel be revoked for health and/or safety reasons.

The HSO, through the HSS, ensures that all personnel entering the (* identify the site) are qualified for downwind deployment, in accordance with the ABC Engineering Co. Health and Safety Program requirements. If the HSO is responsible for a large number of sites, some of these sites may be delegated to Health and Safety Designees (HSDs).

<u>A.1.3 Training</u>

All personnel working on an ABC Engineering Co. site, who may potentially be exposed to toxic substances or hazardous materials, must participate in a 40-hour initial, eight-hour annual (and/or supervisory as appropriate), and site-specific training program in accordance with 29 CFR 1910.120, prior to commencement of their on-site assignment. See Table 2.3-1. Personnel without the required training <u>will not be permitted</u> in a downwind position.

<u>A.1.4 Medical Surveillance</u>

All personnel entering potentially contaminated areas of this site must be medically qualified for site assignment as determined by a medical surveillance program, such as that outlined in the ABC Engineering Co. Health and Safety Program. This program consists of an initial medical examination to establish the employee's baseline, with follow-up examinations conducted on an annual or biennial basis or more frequently if project assignments warrant testing. Personnel without medical clearance <u>will not be permitted</u> in a downwind position.

<u>A.2 SITE CHARACTERIZATION AND ANALYSIS</u>

<u>A.2.1 Site Name, Location, and Size</u>

(*Enter information that identifies the site: its location, city, county, and state; U.S. Geological Survey [USGS] quadrangle; and size. A figure showing the site on a USGS quadrangle or other suitable map would be appropriate.)

A.2.2 Scope of Work

(*Enter information regarding the scope of work as it relates to the types of field activities in which ABC Engineering Co. or subcontractor personnel would be engaged. Particular attention should be given to actual work activities of field personnel to identify where and how they might encounter health and safety hazards.)

A.2.3 Site History

(*Enter information on site use, as it relates to the types of material that could be expected to be encountered during site operations. Information on any site-related incidents, actions, spills, or complaints about the site would be appropriate. A description of existing facilities should be included; a figure of the facility layout, both current and historic, should be inserted, if available.)

A.2.4 Hazardous Substances/Conditions

(*Enter information that would identify those hazardous substances and/or conditions known or suspected to be present on-site. The information could be the result of direct evidence from past environmental actions, or supposition based on historic use of the site. In addition to identifying the hazardous substances that may be present, exposure limits for the substances should be noted along with the sources of the limits. [See Table A-1, Guidelines for Assessing Chemical and Physical Hazards]. It is recommended that the most conservative numbers be used when there is more than a single limit. Other hazardous conditions [e.g., structural instability of site buildings, unstable ground conditions, or explosives] should also be identified). See Table A-2 for Sample of CHRIS Data Sheet/Material Safety Data.

A.2.5 Initial Site Entry

A.2.5.1 Initial Level of Personal Protection

(*Enter information on the selection of the initial level of protection that will be employed for the initial reconnaissance. The selection of this level of protection will be based on the preliminary data collected. If quite a bit is known about the site and its potential hazards, a lower level of personal protection can be selected, if applicable. If little or nothing is known about the site, at a minimum, Level B personal protection must be used [according to OSHA 29 CFR 1910.120(c)]. If this is not a preliminary HASP, this section should be used to discuss the level of protection to be worn initially by site personnel for the proposed site operations.)

A.2.5.2 Initial Monitoring

Where the development of site information either shows the potential for or is unable to rule out the possibility of ionizing radiation or "Immediately Dangerous to Life or Health" (IDLH) conditions, initial monitoring will consist (at a minimum) of an ionizing radiation survey and air monitoring, using devices such as a combustible gas indicator, oxygen meter, or photoionization detector (PID). It is intended that real-time monitoring instrumentation will be used to assist in the determination of the appropriate level of protection for the initial site entry team.

A.2.6 Site Risks

A.2.6.1 Health Hazards

(*Enter information that identifies health hazards that site personnel can expect to encounter as a result of site conditions or operations. This information will be used to support the conclusions in the "Conclusions/Risk Assessment" section, which will be used to select levels of protection identified in Section A.4.3.)

A.2.6.2 Safety Hazards

(*Enter information that identifies safety hazards that site personnel can expect to encounter as a result of site conditions or operations. This information will be used to support the conclusions in the "Conclusions/Risk Assessment" section, which will be used to select levels of protection identified in Section A.4.3.)

A.2.6.3 Conclusions/Risk Assessment

(*Enter the conclusions regarding risk assessment for site personnel, identifying the measures necessary to protect their safety. Areas to consider include the known or suspected contaminants and their potential for additive or synergistic responses, the physical hazards that may be encountered, and the potential for such exposures or encounters to occur.)

A.3 SITE CONTROL

A.3.1 Zonation

(*Insert site layout map showing site zonation.)

The site itself will normally be divided into three zones: the majority of the work area will be considered the Exclusion Zone, with limited areas serving as the Support Zone, and an area for decontamination called the Contamination Reduction Zone (CRZ). See Figure 2.3-1.

A.3.1.1 Exclusion Zone

The Exclusion Zone isolates the area of contaminant generation and restricts (to the extent possible) the spread of contamination from active areas of the site to support areas and off-site locations. The Exclusion Zone is demarcated by the Hot Line (i.e., a tape line or physical barrier). Personnel entering the Exclusion Zone must (1) enter through the CRZ; (2) wear the prescribed level of protection (see Section A.4.3); and (3) be otherwise authorized to enter the Exclusion Zone (see Sections A.1.3, A.1.4, and A.9.1). Any personnel, equipment, or materials exiting the Exclusion Zone will be considered contaminated. Personnel will be subject to decontamination; equipment and materials will be subject to either decontamination or containerization in uncontaminated devices.

Within the Exclusion Zone, specific locations or restricted areas (clearly marked or identified) will be established as necessary for particular locations or around specific site operations. In the case of well drilling or excavation operations, a restricted area will be established that includes a minimum 30-foot radius from the drill rig or excavation operation. Other restricted areas may include drum staging areas, active site areas, sources of combustible gases or air contaminants, or other dangerous areas as they are identified. Specific access for emergency services to areas of specific site operations will be established.

A.3.1.2 Contamination Reduction Zone

Moving out from the Exclusion Zone, starting at the Hot Line and continuing to the Contamination Control Line, is the CRZ. The CRZ is a transition zone between contaminated and uncontaminated areas of the site. When "hot" or contaminated personnel, equipment, or materials cross the Hot Line, they are assumed to be as "hot" or contaminated as they are going to be from site operations. Being subjected to the decontamination process, they become less contaminated; when they reach the Contamination Control Line, they are clean and can exit this zone without spreading contamination.

Within the CRZ is the Contamination Reduction Corridor (CRC), where materials necessary for full personnel and portable equipment decontamination are kept. A separate facility will be established for heavy equipment decontamination. In addition, certain safety equipment (e.g., emergency eye wash, fire extinguisher, stretcher, and first aid kit) is staged in this zone.

A.3.1.3 Support Zone

The Support Zone is the outermost zone of the site, separated from the CRZ by the Contamination Control Line; it is considered a clean area. Movement of personnel and materials from this zone into the CRZ is generally unrestricted, except as required through access points controlled for administrative purposes. However, only uncontaminated/decontaminated personnel or materials may enter this zone from the CRZ.

The Support Zone contains the necessary support facilities (including personal hygiene facilities) for site operations. It also serves as the communications center and source of emergency assistance for operations in the Exclusion Zone and CRZ. A log of all persons entering the site will be maintained by the HSO, the FOL, or the site designee.

A.3.2 Medical Assistance

The primary source of medical assistance for the (*identify the site) is:

> (*identify medical facility)
>
> (*insert address of medical facility)
>
> (*insert telephone number to contact the medical facility or emergency transport to the facility)

The alternate source of medical assistance is:

> (*identify alternate medical facility)
>
> (*insert address of alternate facility)
>
> (*insert telephone number to contact the medical facility or emergency transport to the facility)

A.4 ENGINEERING CONTROLS, WORK PRACTICES, AND PERSONAL PROTECTIVE EQUIPMENT

A.4.1 Engineering Controls

(*Enter a description of the engineering controls that will be employed to deal with the health and safety hazards identified in Section A.2.6. For example, exhaust ventilation systems for fixed work stations, and enclosed, ventilated cabs of heavy equipment and remote-operated equipment.)

A.4.2 Work Practices

(*Enter specific work practices that will be used for this site and site-specific operations. Use the words provided herein, as appropriate.)

Workers are expected to adhere to established safe work practices for their respective specialties (e.g., drilling, laboratory analysis, or construction). The need to exercise caution in the performance of specific work tasks is made more acute due to (1) weather conditions; (2) restricted mobility and reduced peripheral vision caused by the protective gear itself; (3) the need to maintain the integrity of the protective gear; and (4) the increased difficulty in communicating caused by respirators. Work at the site will be conducted according to established protocol and guidelines for the safety and health of all involved. Among the most important of these principles for working at a hazardous waste site are the following:

- In any unknown situation, always assume the worst conditions and plan responses accordingly.

- o Use the buddy system. Under no circumstances will any person be permitted to enter the Exclusion Zone alone. Establish and maintain communication. In addition to radio communications, it is advisable to develop a set of hand signals, because conditions may greatly impair verbal communications.

- o Because no personal protective equipment (PPE) is 100-percent effective, all personnel must minimize contact with excavated or contaminated materials. Plan work areas, decontamination areas, and procedures accordingly. Do not place equipment on drums or the ground. Do not sit on drums or other materials. Do not sit or kneel on the ground in the Exclusion Zone or CRZ. Avoid standing in or walking through puddles, stained soil, or other obvious sources of contamination.

- o Smoking, eating, or drinking in the work area and before decontamination will not be allowed. Oral ingestion of contaminants is the second most likely means of introducing toxic substances into the body (inhalation being the first).
- o Avoid heat and other work stresses related to wearing protective gear. Work breaks should be planned to prevent stress-related accidents or fatigue.

- o To the maximum extent feasible, handling of contaminated materials should be done remotely, particularly when drummed or other containerized hazardous waste materials are found on-site. Every effort should be made to identify the contents of containers found on-site before they are subject to material-handling applications.

- o Personnel must be observant of not only their own immediate surroundings, but also those of others. Everyone will be working under constraints; therefore, a team effort is needed to notice and warn of impending dangerous situations. Extra precautions are necessary when working near heavy equipment and while utilizing PPE because vision, hearing, and communication can be restricted.

- o Contact lenses should not be worn on-site; if corrosive or tear-producing substances enter the eyes, proper flushing would be impeded.

- o Personnel with any facial hair that interferes with the proper fit of the respirator will not be allowed to work on sites requiring Level C or B protection.

- o Rigorous contingency planning and dissemination of plans to all personnel mimimizes the impact of rapidly changing safety protocols in response to changing site conditions.

- o Personnel must be aware that chemical contaminants may mimic or enhance symptoms of other illnesses or intoxication. Avoid excess use of alcohol or working while ill during field investigation assignments.

- o The FOL, HSO, and sampling personnel will maintain project records in a bound notebook (e.g., daily activities, meetings, incidents, and data).

Notebooks will remain on-site for the duration of the project so that replacement personnel can add information, thereby maintaining continuity. These notebooks and daily records should become part of the permanent project file.

A.4.3 Personal Protective Equipment

A.4.3.1 Levels of Protection. The following descriptions provide the basic composition of the generally recognized protective ensembles to be used for site operations. Specific components for any level of protection are site specific and will be selected based on hazard assessment with the ability to upgrade as necessary. Additional elements will be added as necessary. Disposable protective clothing, gloves, and other equipment, exclusive of respirators, should be used when feasible to minimize risks during decontamination, and possible cross-contamination during sample handling. For example, all joints between sleeves and gloves, pant legs and boots, and face mask and hood, should be sealed with duct tape to prevent contaminants from accidentally coming in contact with the skin at these points.

Level A

- o Atmosphere Supplying Respirator (full-facepiece) - either positive pressure Self-Contained Breathing Apparatus [SCBA] or positive pressure Supplied Air Respirator [SAR] (airline) with escape-only positive pressure SCBA.
- o fully-encapsulating, chemical-resistant suit
- o inner chemical-resistant gloves
- o chemical-resistant safety boots/shoes
- o two-way radio (intrinsically safe)
- o cooling unit*
- o coveralls*
- o hardhat*
- o long cotton underwear*

*optional

Level B

- o Atmosphere Supplying Respirator (full-facepiece) - either positive pressure Self-Contained Breathing Apparatus [SCBA] or positive pressure Supplied Air Respirator [SAR] (airline) with escape-only positive pressure SCBA.
- o chemical-resistant clothing (i.e., coveralls and long-sleeved jacket; hooded, one- or two-piece chemical-splash suit; and disposable chemical-resistant one-piece suit)
- o inner and outer chemical-resistant gloves
- o chemical-resistant safety boots/shoes
- o hardhat
- o two-way radio (intrinsically safe)
- o coveralls*
- o disposable boot covers*
- o face shield*
- o long cotton underwear*

Level C

- o full facepiece, air-purifying respirator with appropriate sorbent canisters
- o chemical-resistant clothing (i.e., coveralls and long-sleeved jacket; hooded, one- or two-piece chemical-splash suit; and disposable chemical-resistant one-piece suit)
- o inner and outer chemical-resistant gloves
- o chemical-resistant safety boots/shoes
- o hardhat
- o two-way radio (intrinsically safe)
- o coveralls*
- o disposable boot covers*
- o face shield*

*optional

- o escape mask*
- o long cotton underwear*

Level D

- o coveralls*
- o safety boots/shoes
- o safety glasses or chemical-splash goggles
- o hardhat
- o gloves*
- o escape mask*
- o face shield*
- o boot cover – chemical resistant*

* Optional

A.4.3.2 Other Personal Protective Equipment

(* Enter information that identifies other PPE to be used on-site. Examples include lifelines and harness, personal flotation devices, and body armor for blast protection.)

A.4.3.3 Operational Levels of Protection

(* Enter detailed information regarding the levels of protection that will be employed for each site operation under various site conditions, emphasizing the points or factors that will necessitate a higher level of protection. The information developed in Sections A.2.2 through A.2.6 should be used to determine the levels of protection needed for the proposed site operations. NOTE: The protection described in this section must be supported by the conclusions in the "Conclusions/Risk Assessment" section.)

A.5 MONITORING

The work environment will be monitored to ensure that IDLH or other dangerous conditions are identified. At a minimum, monitoring will include evaluations for combustible atmospheres, oxygen-deficient environments, hazardous concentrations of airborne contaminants, and radioactivity.

A.5.1 Air Sampling: Equipment, Calibration, and Maintenance

To the extent feasible, the presence of airborne contaminants will be evaluated through the use of direct-reading instrumentation. Information gathered will be used to ensure the adequacy of the levels of protection being employed at the site, and may be used as the basis for upgrading or downgrading levels of protection, at the discretion of the site HSO.

(*Identify the air sampling equipment to be used at the site, and the frequency at which it will be employed [i.e., during initial site visit, daily at the start-up of operations, constantly during operations, or some combination thereof]. Examples of the types of air monitoring equipment currently available for site operations follow.)

- ISD Dual Detector:

  This meter monitors for combustible gases and oxygen. It can be used to determine (1) if an area contains concentrations of combustible gases with readings in percentage of the lower explosive limit; and (2) the percentage of oxygen. This equipment will be calibrated in accordance with the manufacturer's instructions.

- NMS MX-241 (Explosimeter):

  This instrument, which is calibrated to methane, monitors combustible gases in the percentage of the lower explosive limit. It will be calibrated in accordance with the manufacturer's instructions.

- ISD HS267:

  This instrument monitors for the presence of hydrogen sulfide in parts per million (ppm). This instrument will be calibrated in accordance with the manufacturer's instructions.

- Photovac Organic Vapor Analyzer (OVA) 10S50:

  The OVA is a total organic vapor analyzer capable of detecting volatile organic compounds (VOCs) that can be ionized by ultraviolet (UV) light. Model 10S50 is commonly used on-site to estimate the presence of VOCs for purposes of crew protection, well screen placement, and selection of samples for further analysis. The principle of operation is twofold: (1) the ambient temperature gas chromatograph (GC), which resolves mixtures of VOCs into individual components identified by retention time; and (2) detection accomplished by ionization in UV light. The charged component then moves to an electrode, which, in turn, results in a meter deflection proportional to the concentration of the contaminant. This instrument does not read out directly in ppm unless calibrated against the material being measured; therefore, results must be interpreted carefully and conservatively. Calibration and maintenance will be performed in accordance with the manufacturer's instructions.

- o HNU PI101 and Photovac TIP Photoionization Detector (PID):

  Like the OVA, the PID operates on the basis of ionization of the contaminant, which results in a meter deflection proportional to the concentration of the contaminant. In the PID, ionization is caused by a UV light source. The strength of the UV light (measured in electron volts [eV]) determines which contaminants can be ionized. The HNU can use three different-strength UV sources: 9.6, 10.2, and 11.7 eV. Only the 10.2- and 11.7-eV probes are currently available for field use. The TIP operates using a UV light source of 10.6 eV. Calibration and maintenance will be performed in accordance with the manufacturer's instructions.

- o Detector Tubes (MSA and Draeger):

  A colorimetric detector tube is a direct-reading instrument that consists of a glass tube impregnated with an indicating chemical, which is connected to a piston cylinder or bellows-type pump. A known volume of air is drawn through the glass tube. The contaminant in the air reacts with the indicator chemical, producing a stain, the length of which is proportional to the contaminant's concentration. Care must be taken when using the detector tubes because reliability of the results depends on proper calibration, the degree of stability of the reacting chemical, and the ambient temperature. Interfering gases or vapors can also positively or negatively affect measured results. Calibration should be carried out according to the manufacturer's instructions.

A.5.2 Personal Monitoring: Equipment, Maintenance, and Calibration

Personal monitoring will be undertaken to characterize exposure of high-risk employees to hazardous substances encountered on-site. The designation of an employee as high-risk will be the responsibility of the HSO in consultation with the HSS and or HSM.
(*Identify the personal monitoring equipment to be used on-site, and the frequency that it will be employed [i.e., during initial site visit, daily at the start-up of operations, constantly during operations, or some combination thereof]. Examples of the types of personal monitoring equipment currently available for site operations follow.)

- o Gilian Personal Sampling Pumps: These devices can be worn by an employee to draw air samples through appropriate collection media. The units can be used to draw volumes from 2 to 3 liters per minute. Calibration will be conducted using standard industrial hygiene protocols before and after each sampling session (i.e., each day's use).

- o Passive Dosimeters or Gas Badges: These devices are non-mechanical collection devices used to monitor for organic vapors and various gases. They are worn by an employee and sent to an industrial hygiene laboratory for analysis.

- o Thermoluminescent Dosimetry (TLD) Body Badges: These devices are non-mechanical collection devices used to monitor for x-ray, beta, and gamma radiation exposure. They are worn by an employee and sent to a qualified laboratory for analysis.

A.5.3 Other

(*Identify any other sampling equipment that will be used to evaluate potential employee exposures on-site.)

A.6 DECONTAMINATION/DISPOSAL

All personnel and/or equipment leaving contaminated site areas are subject to decontamination, which occurs in the CRZ (see Section A.3.1).

A.6.1 Personnel Decontamination

(*Enter information regarding the personnel decontamination equipment and requirements for the site based on the level of protection used. A figure showing the decontamination line layout should be included; examples of figure types can be found in Appendix 1 of the USEPA Standard Operating Safety Guides. The following words can be used as is or adjusted to the site.)

Decontamination procedures must be followed by all personnel leaving hazardous waste sites. When using Level A or B personal protection, decontamination will be a team effort, with the decontamination team at a level of protection equal to or one level lower than the work crew. Under no circumstances (except emergency evacuation) will personnel be allowed to leave the site prior to decontamination. Generalized procedures for removal of protective clothing are as follows:

1. Drop tools, monitors, samples, and trash at designated drop stations (i.e., plastic containers or drop sheets).

2. Step into the designated shuffle pit area and scuff feet to remove gross amounts of dirt from outer boots. Wash down boots with clear water in the designated wash pit area. If non-disposable clothing is used, wash down outer protective garments.

3. Remove tape from boots and remove boots; discard in disposal container.

4. Remove outer gloves and place in container.

5. Remove hardhat and respirator and place or hang in the designated area.

6. Remove outer garment and discard in container.

7. Remove inner gloves and discard in container.

8. If the site requires use of a decontamination trailer, all personnel must shower before leaving the site at the end of the work day.

NOTE: Disposable items (i.e., Tyvek coveralls, inner gloves, and latex overboots) will be changed on a daily basis unless there is reason to change sooner. Dual respirator canisters will be changed daily, unless more frequent changes are deemed appropriate by site surveillance data or personnel assessment.

Pressurized sprayers or other designated equipment will be available in the decontamination area for wash down and cleaning of personnel, samples, and equipment.

Respirators will be decontaminated daily and taken from the drop area. The masks will be disassembled, the cartridges set aside, and all other parts placed in a cleansing solution. Parts will be pre-coded (e.g., #1 on all parts of Mask #1). After an appropriate time in the solution, the parts will be removed and rinsed with potable water. Old cartridges will be marked to indicate length of usage (i.e., if means to evaluate the cartridges' remaining utility are available) or will be discarded in the contaminated trash container for disposal. In the morning, the masks will be reassembled and new cartridges installed, if appropriate. Personnel will inspect their own masks and readjust the straps for proper fit.

A.6.2 Small Equipment Decontamination

(*Enter information that establishes decontamination procedures for small equipment [e.g., hand tools, radios, instruments, or other small non-disposable items the field crew might use downrange]. This could include bagging or wrapping of equipment prior to sending it downrange. The following words can be used, as appropriate.)

Small equipment will be protected from contamination as much as possible by draping, masking, or otherwise covering the instruments with plastic (to the extent feasible) without hindering operation of the unit. For example, the HNU meter should be placed in a clear plastic bag to allow reading the scale and operating the knobs. The HNU sensor should be partially wrapped, keeping the sensor tip and discharge port clear.

The contaminated equipment will be taken from the drop area and the protective coverings removed and disposed of in appropriate containers. Any dirt or obvious contamination will be brushed or wiped with a disposable paper wipe. The units can then be taken inside in a clean plastic tub, wiped off with damp disposable wipes, and dried. The units will be checked, standardized, and recharged as necessary for the next day's operation, and then prepared with new protective coverings.

A.6.3 Heavy Equipment Decontamination

(*Enter information that defines how heavy equipment used on-site will be decontaminated before being permitted to leave the site. This must include the mechanism for controlling and/or collecting the fluids used for heavy equipment decontamination. A figure showing the layout of a heavy equipment decontamination station can be used. The following words can be used, as appropriate.)

It is anticipated that drilling rigs/backhoes will be contaminated during borehole/test-pitting activities. They will be cleaned with high-pressure water or steam, followed by a soap-and-water wash and rinse. Loose material will be removed with a brush. The person performing this activity will usually be at least at the level of protection utilized during the personnel and monitoring equipment decontamination.

A decontamination pad will be constructed to allow collection and storage of contaminated decontamination fluids in Department of Transportation (DOT)-approved 55-gallon drums.

A.6.4 Disposal of Decontaminated Materials

(*All contaminated disposable clothing and decontamination fluids must be properly handled on-site. For those sites where disposal has not yet occurred, these fluids and materials may be left on-site, when properly containerized. At other sites, it may be necessary to containerize and dispose of the materials as Hazardous Wastes Solids or Hazardous Wastes Liquids not otherwise stated (n.o.s.). As a result of the need to do something with these materials, this section must state how they will be handled and disposed of. The following words can be used, as appropriate.)

All protective gear, decontamination fluids (for both personnel and equipment), and other disposable materials will be disposed of at each site. Decontamination fluids (i.e., methylhydrate [ethanol:methanol 9:1 v/v], used to decontaminate sampling equipment [e.g., split spoons and groundwater sampling pump]) will be stored in DOT-approved 55-gallon drums. Disposable materials (e.g., gloves and Tyveks) will be double-bagged and stored as is, or placed in DOT-approved 55-gallon drums.

A.7 EMERGENCY/CONTINGENCY PLAN

(*As now envisioned, this HASP would be used for operations at sites for Remedial Investigations/Feasibility Studies [RIs/FSs] or remediation efforts. As such, the emergency/contingency plan required under 29 CFR 1910.120 would be for "on-site emergency response" only. Much of the information required by 1910.120[i] is found in other sections of the HASP; therefore, only those items not previously addressed are included in this section. In the event that such information is not considered necessary, specifically indicate this. DO NOT LEAVE BLANKS IN THE HASP.)

This section identifies the emergency contingency planning undertaken for operations at this site. Other sections provide further information to be used under emergency conditions.

A.7.1 Personnel Roles, Lines of Authority, and Communications

The site HSO is the primary authority for directing site operations under emergency conditions. All communications both on- and off-site will be directed through the HSO.

A.7.2 Evacuation

(*The need to evacuate, and the location where site workers will be safe if an evacuation is necessary, will depend on the type of emergency [i.e., fire, explosion, chemical release, or personal injury]. Therefore, include information that identifies the contingency being planned for. For example, in the event of a FIRE, when the decision to evacuate is made, personnel will evacuate upwind to location "X" and await further instruction. In the event of a CHEMICAL RELEASE, when the decision to evacuate is made, personnel will move to an upwind position [as noted by a windsock] relative to the release. The following words can be used, as appropriate.)

A.7.2.1 Withdrawal Upwind

The work party will continually note general wind directions while on-site. (A windsock may be set up near the work site for visual determinations.) When conditions warrant moving away from the work site, the crew will relocate upwind a distance of approximately 100 feet or farther, as indicated by site monitoring instruments. Donning a SCBA and a safety harness and line, the HSO or a member of the crew may return to the work site to determine if the condition noted was transient or persistent. If persistent, an alarm should be raised to notify on-site personnel of the situation and the need to leave the site or don a SCBA. An attempt to decrease emissions should be made only if greater respiratory protection is donned. The HSO and client will be notified of conditions. When site access is restricted, thus hindering escape, the crew may be instructed to evacuate the site rather than move upwind, especially if withdrawal upwind moves the crew away from escape routes.

A.7.2.2 Site Evacuation

When conditions warrant site evacuation, the work party will proceed upwind of the work site and notify the security force, HSO, and field office of site conditions. If the decontamination area is upwind and greater than 500 feet from the work site, the crew will pass quickly through decontamination to remove contaminated outer suits. If the hazard is toxic gas, respirators will be retained. The crew will proceed to the field office to assess the situation. If instrumentation indicates an acceptable condition, respirators may be removed. As more information is received from the field crew, it will be relayed to the appropriate agencies. The advisability and type of further response action will be coordinated and carried out by the HSO.

A.7.2.3 Evacuation of Surrounding Area

When the HSO determines that conditions warrant evacuation of downwind residences and commercial operations, local agencies will be notified and assistance requested. Designated on-site personnel will initiate evacuation of the immediate off-site area without delay.

A.7.3 Emergency Medical Treatment/First Aid

(*Provisions must be made for adequate numbers of site personnel, trained to render first aid and CPR; these persons should be identified in this section. Additionally, specific pages of the HASP, found in Section A.9, are designed as pull-outs for posting information [e.g., emergency telephone numbers and routes to medical services].)

First aid will be rendered to any person injured on-site, as appropriate. The injured person will then be transported to medical personnel for further examination and/or treatment. The preferred transport method is a professional emergency transportation service; however, when this is not readily available or would result in excessive delay, other transport is authorized. Under no circumstances will injured persons transport themselves to a medical facility for emergency treatment.

When an injury occurs in a downrange position, provisions for decontamination of the victim will be made. However, life-threatening conditions may preclude normal decontamination procedures. In such cases, arrangements will be made with the medical facility and transporter to provide for the situation.

A.8.0 OTHER

(*Enter information on other site topics that are not appropriately discussed in separate sections of the HASP. All sections must be addressed. If not applicable, state this. DO NOT LEAVE BLANKS IN THE HASP.)

A.8.1 Illumination

Site operations will not be permitted without adequate lighting. Therefore, unless provisions are made for artificial light, downrange operations must halt in time to permit personnel and equipment to exit the Exclusion Zone and proceed through decontamination before dusk. Conversely, operations will not be permitted to begin until lighting is adequate.

(*If artificial light is to be used, information about the types and deployment should be included.)

A.8.2 Sanitation

(*Provisions must be made for sanitation facilities for the site work force. At a minimum, the provision of toilet facilities must meet the requirements of 29 CFR 1910.120(n), which include one facility for less than 20 employees; or one toilet and one urinal for every 40 employees, up to 200; then one of each for every 50 employees. If it is a mobile crew and they have transport readily available, the requirements do not apply.)

A.8.3 Excavation

Site excavations created during site operations will be shored or sloped to prevent accidental collapse, and otherwise conducted in accordance with 29 CFR 1926 (Subpart P). Under no circumstances will site personnel enter excavations that are not adequately shored or sloped. When entry into an excavation does occur, and the excavation is considered a confined space, such an entry will be done in accordance with the confined space entry program (see Section A.8.4).

A.8.4 Confined Space Entry

Confined space entry presents special problems and substantial risks to involved personnel (*including those who might be called upon to attempt a rescue of initial entrants). Therefore, entry into a confined space is a MEANS OF LAST RESORT, and will only be permitted where no other mechanism is feasible to achieve the desired goal. If confined space entry is necessary, it will be conducted under provisions outlined in Attachment 1.

A.8.5 OSHA Poster

OSHA requires employers to post the "Job Safety and Health Protection" poster in a conspicuous place where notices to employees are customarily posted. This includes trailers at job sites. The purpose of the poster is to inform employees of their rights under the Occupational Safety and Health Act. Figure A-1 contains a copy of this poster.

A.9 ADMINISTRATIVE

A.9.1 Personnel Authorized Downrange

Personnel authorized to participate in downrange activities at this site have been reviewed and certified for site operations by the Site Manager and HSS. Certification involves the completion of appropriate training, a medical examination, and a review of this site-specific HASP. All persons entering the site must utilize the buddy system, and check in with the Site Manager and/or HSO before proceeding downrange.

Certified ABC Engineering Co. Team Personnel:

______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________

Other Certified Personnel

______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________

* Current First Aid Training
\+ Current CPR Training

A.9.2 Health and Safety Plan Approvals

By signature, the undersigned approve this HASP for applicability in the protection of the health and safety of all persons entering the (identify the site).

____ ___________________
Health and Safety Officer Date

____ ___________________
Project Manager Date

____ ___________________
ABC Engineering Co. Health and Safety Manager/Supervisor Date

A.9.3 Emergency Telephone Numbers

(Local) Police Department	( ) -
(Local) Rescue Service	( ) -
(*insert name of primary) hospital	( ) -
(*insert name of secondary) hospital	( ) -
(Local) Fire Department	( ) -
Off-site Emergency Services	( ) -
National Poison Control Center	(800) 492-2414
Massachusetts Poison Control Center	(800) 682-9211
National Response Center	(800) 424-8802
Regional USEPA Emergency Response	( ) -
Chemical Manufacturers Association	
Chemical Referral Center	(800) 262-8200
Site Health and Safety Officer: (* enter name of HSO)	( ) -
Site Manager: (*insert name)	( ) -
Regional Health and Safety Supervisor: (*insert name)	( ) -
ABC Environmental Co. Health and Safety Manager: (*insert name)	( ) -

A.9.4 Routes to Emergency Medical Facilities

Primary source of medical assistance for the (* identify the site):

(* identify medical facility)

(* insert address of medical facility)

(* insert telephone number to contact the medical facility for emergency transport to the facility)

Directions to primary source of medical assistance:

(* insert directions to primary medical facility)

Alternate source of medical assistance:

(* identify alternate medical facility)

(* insert address of alternate facility)

(* insert telephone number to contact the medical facility or emergency transport to the facility)

Directions to alternate source of medical assistance:

(* insert directions to alternate medical facility)

(* Insert area map showing routes to primary and alternate medical facilities, on a separate page if necessary.)

A.9.5 Emergency Signals

In most cases, field personnel will carry portable radios for communications. If this is the case, a transmission that indicates it is of an emergency nature will take priority over all other transmissions. All other site radios will yield the frequency to the emergency transmissions.

Where radio communication is not available, the following air-horn signals will be used:

HELP	three short blasts	(. . .)
EVACUATION	three long blasts	(___ ___ ___)
ALL CLEAR	alternating long and short blasts	(___.___.___)

(* Enter any other site-specific emergency signals deemed necessary.)

A.9.6 Field Team Review

I have read and reviewed the HASP for the (* identify the site), understand the information contained, and agree to comply.

Site/Project: ____

Name: ________________________________ Date: ______________
(Please Print)

Signature: ____

A.9.7 Medical Data Sheet

This Medical Data Sheet will be completed by all on-site personnel and will be kept in the Support Zone during site operations. It is in no way a substitute for the Medical Surveillance Program requirements consistent with the ABC Engineering Co. Health and Safety Program for Hazardous Waste Sites. This data sheet will accompany any personnel when medical assistance or transport to hospital facilities is required. If more information is required, use the back of this sheet.

Project: ____

Name: ____

Address: ____

Home Telephone: ( )________________________

DOB: _______________ Height: __________ Weight: ______________

In case of emergency, contact: ______________________________
(print name)

Address: ____

____

Telephone (Day): ( ) ______________________________________

Telephone (Night): ( ) ______________________________________

Do you wear contacts? ( ) Yes ( ) No

Allergies: ____

List medication taken regularly: ______________________________

Particular sensitivities: ______________________________________

Previous/recent illnesses or exposures to hazardous chemicals:
____

Name of Personal Physician ______________________________________

Telephone: ( ) ____

JOB SAFETY & HEALTH PROTECTION

The Occupational Safety and Health Act of 1970 provides job safety and health protection for workers by promoting safe and healthful working conditions throughout the Nation. Requirements of the Act include the following:

Employers

All employers must furnish to employees employment and a place of employment free from recognized hazards that are causing or are likely to cause death or serious harm to employees. Employers must comply with occupational safety and health standards issued under the Act.

Employees

Employees must comply with all occupational safety and health standards, rules, regulations and orders issued under the Act that apply to their own actions and conduct on the job.

The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor has the primary responsibility for administering the Act. OSHA issues occupational safety and health standards, and its Compliance Safety and Health Officers conduct jobsite inspections to help ensure compliance with the Act.

Inspection

The Act requires that a representative of the employer and a representative authorized by the employees be given an opportunity to accompany the OSHA inspector for the purpose of aiding the inspection.

Where there is no authorized employee representative, the OSHA Compliance Officer must consult with a reasonable number of employees concerning safety and health conditions in the workplace.

Complaint

Employees or their representatives have the right to file a complaint with the nearest OSHA office requesting an inspection if they believe unsafe or unhealthful conditions exist in their workplace. OSHA will withhold, on request, names of employees complaining.

The Act provides that employees may not be discharged or discriminated against in any way for filing safety and health complaints or for otherwise exercising their rights under the Act.

Employees who believe they have been discriminated against may file a complaint with their nearest OSHA office within 30 days of the alleged discrimination.

Citation

If upon inspection OSHA believes an employer has violated the Act, a citation alleging such violations will be issued to the employer. Each citation will specify a time period within which the alleged violation must be corrected.

The OSHA citation must be prominently displayed at or near the place of alleged violation for three days, or until it is corrected, whichever is later, to warn employees of dangers that may exist there.

Proposed Penalty

The Act provides for mandatory penalties against employers of up to $1,000 for each serious violation and for optional penalties of up to $1,000 for each nonserious violation. Penalties of up to $1,000 per day may be proposed for failure to correct violations within the proposed time period. Also, any employer who willfully or repeatedly violates the Act may be assessed penalties of up to $10,000 for each such violation.

Criminal penalties are also provided for in the Act. Any willful violation resulting in death of an employee, upon conviction, is punishable by a fine of not more than $10,000, or by imprisonment for not more than six months, or by both. Conviction of an employer after a first conviction doubles these maximum penalties.

Voluntary Activity

While providing penalties for violations, the Act also encourages efforts by labor and management, before an OSHA inspection, to reduce workplace hazards voluntarily and to develop and improve safety and health programs in all workplaces and industries. OSHA's Voluntary Protection Programs recognize outstanding efforts of this nature.

Such voluntary action should initially focus on the identification and elimination of hazards that could cause death, injury, or illness to employees and supervisors. There are many public and private organizations that can provide information and assistance in this effort, if requested. Also, your local OSHA office can provide considerable help and advice on solving safety and health problems or can refer you to other sources for help such as training.

Consultation

Free consultative assistance, without citation or penalty, is available to employers, on request, through OSHA supported programs in most State departments of labor or health.

AUGUSTA AREA OFFICE
FEDERAL BLDG & P. O.
40 WESTERN AVE., RM. 121
AUGUSTA, MAINE
TEL (207) 622-

More Information

Additional information and copies of the Act, specific OSHA safety and health standards, and other applicable regulations may be obtained from your employer or from the nearest OSHA Regional Office in the following locations:

Atlanta, Georgia
Boston, Massachusetts
Chicago, Illinois
Dallas, Texas
Denver, Colorado
Kansas City, Missouri
New York, New York
Philadelphia, Pennsylvania
San Francisco, California
Seattle, Washington

Telephone numbers for these offices, and additional area office locations, are listed in the telephone directory under the United States Department of Labor in the United States Government listing.

Washington, D.C.
1985
OSHA 2203

William E. Brock, Secretary of Labor

U.S. Department of Labor
Occupational Safety and Health Administration

Under provisions of Title 29, Code of Federal Regulations, Part 1903.2(a)(1) employers must post this notice (or a facsimile) in a conspicuous place where notices to employees are customarily posted.

Figure A-1

OSHA Job Safety and Health Protection Poster.

Table A-1

CHRIS DATA SHEETS/MATERIAL SAFETY DATA SHEETS
FOR CONTAMINANTS OF CONCERN

TRICHLOROETHYLENE

TCL

Common Synonyms
Trichloroethylene
Triclene, Algylen
Chlorylen
Gemalgene
Trethylene
Trichloran, Trilene

Watery liquid — Colorless — Sweet odor

Sinks in water. Irritating vapor is produced.

Stop discharge if possible. Keep people away.
Avoid contact with liquid and vapor.
Call fire department.
Isolate and remove discharged material.
Notify local health and pollution control agencies.

Fire

Combustible.
POISONOUS GASES ARE PRODUCED IN FIRE.
Wear goggles and self-contained breathing apparatus.
Extinguish with dry chemical, carbon dioxide, or foam.

Exposure

CALL FOR MEDICAL AID.

VAPOR
Irritating to eyes, nose and throat.
If inhaled, will cause nausea, vomiting, difficult breathing, or loss of consciousness.
Move to fresh air.
If breathing has stopped, give artificial respiration.
If breathing is difficult, give oxygen.

LIQUID
Irritating to skin and eyes.
If swallowed, will cause nausea, vomiting, difficult breathing, or loss of consciousness.
Remove contaminated clothing and shoes.
Flush affected areas with plenty of water.
IF IN EYES, hold eyelids open and flush with plenty of water.
IF SWALLOWED and victim is CONSCIOUS, have victim drink water or milk and have victim induce vomiting.
IF SWALLOWED and victim is UNCONSCIOUS OR HAVING CONVULSIONS, do nothing except keep victim warm.

Water Pollution

Effect of low concentrations on aquatic life is unknown.
May be dangerous if it enters water intakes.
Notify local health and wildlife officials.
Notify operators of nearby water intakes.

1. RESPONSE TO DISCHARGE
(See Response Methods Handbook)
Should be removed
Chemical and physical treatment

2. LABEL
2.1 **Category:** None
2.2 **Class:** Not pertinent

3. CHEMICAL DESIGNATIONS
3.1 **CG Compatibility Class:** Halogenated hydrocarbon
3.2 **Formula:** $CHCl{=}CCl_2$
3.3 **IMO/UN Designation:** 9.0/1710
3.4 **DOT ID No.:** 1710
3.5 **CAS Registry No.:** 79-01-6

4. OBSERVV^LE CHARACTERISTICS
4.1 **Physical State (as shipped):** Liquid
4.2 **Color:** Colorless
4.3 **Odor:** Chloroform-like; ethereal

5. HEALTH HAZARDS
5.1 **Personal Protective Equipment:** Organic vapor-acid gas canister; self-contained breathing apparatus for emergencies; neoprene or vinyl gloves; chemical safety goggles, face-shield; neoprene safety shoes; neoprene suit or apron for splash protection.
5.2 **Symptoms Following Exposure:** INHALATION: symptoms range from irritation of the nose and throat to nausea, an attitude of irresponsibility, blurred vision, and finally disturbance of central nervous system resulting in cardiac failure. Chronic exposure may cause organic injury. INGESTION: symptoms similar to inhalation. SKIN: defatting action can cause dermatitis. EYES: slightly irritating sensation and lachrymation.
5.3 **Treatment of Exposure:** Do NOT administer adrenalin or epinephrine; get medical attention for all cases of overexposure. INHALATION: remove victim to fresh air; if necessary, apply artificial respiration and/or administer oxygen. INGESTION: have victim drink water and induce vomiting; repeat three times; then give 1 tablespoon epsom salts in water. EYES: flush thoroughly with water. SKIN: wash thoroughly with soap and warm water.
5.4 **Threshold Limit Value:** 50 ppm
5.5 **Short Term Inhalation Limits:** 200 ppm for 30 min.
5.6 **Toxicity by Ingestion:** Grade 3; LD_{50} = 50 to 500 mg/kg
5.7 **Late Toxicity:** Data not available
5.8 **Vapor (Gas) Irritant Characteristics:** Vapors cause a slight smarting of the eyes or respiratory system if present in high concentrations. The effect is temporary.
5.9 **Liquid or Solid Irritant Characteristics:** Minimum hazard. If spilled on clothing and allowed to remain, may cause smarting and reddening of the skin.
5.10 **Odor Threshold:** 50 ppm
5.11 **IDLH Value:** 1,000 ppm

6. FIRE HAZARDS
6.1 **Flash Point:** 90°F C.C.; practically nonflammable
6.2 **Flammable Limits in Air:** 8.0%-10.5%
6.3 **Fire Extinguishing Agents:** Water fog
6.4 **Fire Extinguishing Agents Not to be Used:** Not pertinent
6.5 **Special Hazards of Combustion Products:** Toxic and irritating gases are produced in fire situations.
6.6 **Behavior in Fire:** Not pertinent
6.7 **Ignition Temperature:** 770°F
6.8 **Electrical Hazard:** Not pertinent
6.9 **Burning Rate:** Not pertinent
6.10 **Adiabatic Flame Temperature:** Data not available
6.11 **Stoichiometric Air to Fuel Ratio:** Data not available
6.12 **Flame Temperature:** Data not available

7. CHEMICAL REACTIVITY
7.1 **Reactivity With Water:** No reaction
7.2 **Reactivity with Common Materials:** No reaction
7.3 **Stability During Transport:** Stable
7.4 **Neutralizing Agents for Acids and Caustics:** Not pertinent
7.5 **Polymerization:** Not pertinent
7.6 **Inhibitor of Polymerization:** Not pertinent
7.7 **Molar Ratio (Reactant to Product):** Data not available
7.8 **Reactivity Group:** 36

8. WATER POLLUTION
8.1 **Aquatic Toxicity:** 850 mg/l/40 hr/daphnia/kill/fresh water
8.2 **Waterfowl Toxicity:** Data not available
8.3 **Biological Oxygen Demand (BOD):** Data not available
8.4 **Food Chain Concentration Potential:** None

9. SHIPPING INFORMATION
9.1 **Grades of Purity:** Technical; dry cleaning; degreasing; extraction
9.2 **Storage Temperature:** Ambient
9.3 **Inert Atmosphere:** No requirement
9.4 **Venting:** Pressure-vacuum

10. HAZARD ASSESSMENT CODE
(See Hazard Assessment Handbook)
A-X-Y

11. HAZARD CLASSIFICATIONS
11.1 **Code of Federal Regulations:** ORM-A
11.2 **NAS Hazard Rating for Bulk Water Transportation:**

Category	Rating
Fire	1
Health	
Vapor Irritant	1
Liquid or Solid Irritant	1
Poisons	2
Water Pollution	
Human Toxicity	1
Aquatic Toxicity	2
Aesthetic Effect	2
Reactivity	
Other Chemicals	1
Water	0
Self Reaction	1

11.3 **NFPA Hazard Classification:**

Category	Classification
Health Hazard (Blue)	2
Flammability (Red)	1
Reactivity (Yellow)	0

12. PHYSICAL AND CHEMICAL PROPERTIES
12.1 **Physical State at 15°C and 1 atm:** Liquid
12.2 **Molecular Weight:** 131.39
12.3 **Boiling Point at 1 atm:** 189°F = 87°C = 360°K
12.4 **Freezing Point:** −123.5°F = −86.4°C = 186.8°K
12.5 **Critical Temperature:** Not pertinent
12.6 **Critical Pressure:** Not pertinent
12.7 **Specific Gravity:** 1.46 at 20°C (liquid)
12.8 **Liquid Surface Tension:** 29.3 dynes/cm = 0.0293 N/m at 20°C
12.9 **Liquid Water Interfacial Tension:** 34.5 dynes/cm = 0.0345 N/m at 24°C
12.10 **Vapor (Gas) Specific Gravity:** 4.5
12.11 **Ratio of Specific Heats of Vapor (Gas):** 1.116
12.12 **Latent Heat of Vaporization:** 103 Btu/lb = 57.2 cal/g = 2.4×10^5 J/kg
12.13 **Heat of Combustion:** Not pertinent
12.14 **Heat of Decomposition:** Not pertinent
12.15 **Heat of Solution:** Not pertinent
12.16 **Heat of Polymerization:** Not pertinent
12.25 **Heat of Fusion:** Data not available
12.26 **Limiting Value:** Data not available
12.27 **Reid Vapor Pressure:** 2.5 psia

NOTES

Table A-1

Sample of CHRIS Data Sheet/Material Safety Data Sheet for Contaminants of Concern

ATTACHMENT 1

CONFINED SPACE ENTRY PROCEDURES

Refer to
"Confined Space Entry Program" for further information

(TO BE INCLUDED WITH THE HASP FOR
ALL CONFINED SPACE ENTRY WORK)

CONFINED SPACE CLASSIFICATION

Confined spaces are classified according to their existing or potential chemical and physical hazards. Classification is based on characteristics of the confined space, oxygen level, flammability, and toxicity. The following table defines the parameters of each classification. If any of the hazards present a situation that is "Immediately Dangerous to Life and Health" (IDLH), the confined space is classified as Class A. Classification is determined by the most hazardous condition of entering, working in, and exiting a confined space. Class B confined spaces have the potential for causing injury and illness but are not IDLH. Class C entry is one in which the chemical hazard potential is minimal and does not require any special modification in work procedures. (See Table A-2)

ENTRY PROCEDURES

Team Size. A minimum of three workers is required for each confined space activity: two entry and one standby; or one entry, one rescue, and one standby. If the former is used, all three must be ABC Engineering Co. employees. If the latter is used, the standby could be a non-ABC Engineering Co. team member, assuming he/she has comparable training, is proficient in the assigned duties, and is capable of using all safety equipment.

The one entry/one rescue/one standby arrangement should only be used when the confined space is relatively small and/or the entry person will be in the line of sight at all times. In this instance, the rescue person acts as the second person in the "buddy system."

The two entry/one standby arrangement is used when the area of the confined space is larger, and the tasks may take the worker away from the entryway. Again, care must be taken with this arrangement because the standby person cannot enter the confined space and attempt rescue unless adequately protected (i.e., respiratory and dermal) and replaced by another qualified standby person.

This number of workers is the minimum required for these activities and, in most cases, should only be used for relatively nonhazardous confined spaces. Additional crew may be needed if entering a Class A or B confined space. Additional crew could include rescue, decontamination, and line-of-sight personnel.

General Entry

1. Inspect all pieces of equipment to ensure they are in good working order. DO NOT ENTER A CONFINED SPACE WITH DEFECTIVE EQUIPMENT.

2. Conduct a background check to identify all potential hazards that may be encountered in the confined space. Determine if there is a potential for fire/explosion hazards, as well as a potential for a toxic or oxygen-deficient atmosphere.

3. Test the atmosphere inside the confined space before entry. An attempt should be made to test the atmosphere without opening the entryway (i.e., through a vent line or a small opening). If the entryway must be opened to test, and only low levels are expected in the confined space, crack open entryway, test breathing zone first, and then test the confined space. If potentially high levels are expected in the breathing zone, respiratory protection should be worn prior to opening the entryway cover.

4. Purge or ventilate the confined space prior to entry, if explosive, toxic, or oxygen-deficient atmosphere is detected. Retest the atmosphere three times at 5-minute intervals. A person can enter the confined space without respiratory protection only if all three test results are below the Permissible Exposure Limit/Threshold Limit Value (PEL/TLV), 10 percent of the Lower Explosive Limit (LEL), and above 19.5-percent oxygen (all three conditions must be met).

   (NOTE: <u>Any</u> downward deflection of the readings on the oxygen meter from background (i.e., 20.9 percent) should be viewed as a potential for an IDLH atmosphere. Unless contaminants are known to be nontoxic, do not enter the confined space without respiratory protection if the oxygen level is below background.)

5. Blank, block, or otherwise isolate, lockout, and tag all chemical, physical, and/or electrical hazards wherever possible.

6. Monitor the air on a continuous basis, if using an air-purifying respirator or if an IDLH and/or explosive atmosphere exists. If respiratory protection is not used and there is potential for atmospheric conditions to change due to work practices or conditions, air monitoring should be done periodically. In all these cases, a 5-minute escape pack must be used.

7. Record all results of the tests for hazardous conditions including the location, time, date, weather (if applicable), and readings on the PID, combustible gas meter, oxygen deficiency meter, Draeger tubes, and any other equipment used on the "Confined Space Entry Checklist-General Entry" form. Send a copy of the completed form to the Health and Safety Supervisor (HSS).

8. Wear appropriate clothing for site conditions, as determined by the Health and Safety Officer (HSO).

9. Wear a safety belt or harness with lifeline if hazardous conditions exist. If the diameter of the entryway is less than 18 inches, the wrist-type harness must be used and special provisions made if a supplied-air respirator is necessary.

10. One person (standby) must remain at the entryway at all times and must keep continuous contact with the person entering the confined space. Contact can be maintained by line of sight, listening for sounds, the safety line, and/or radio. The standby person must not enter the confined space unless another trained person

is available to act as standby, and he/she is equipped with adequate respiratory and dermal protection. (In most cases, respiratory protection would be an airline respirator or self-contained breathing apparatus [SCBA].)

11. Do not smoke when working in or near confined spaces and do not take flash-lighted photographs when explosive gases are known or suspected to be present.

12. Do not rely on permanent ladders because they are often in poor condition. If they must be used, be sure of footing. Inspect permanent ladders for deterioration before entering and while descending. Try each step with one foot, while standing on the step above. When in doubt, use a portable ladder of adequate height to reach 3 feet above opening, or a rope ladder, or lower the entry person using the tripod. If a portable ladder is used, it should be tied off, if possible; otherwise, it should be held in place by the standby person.

13. Do not work with inadequate lighting. Use only "explosion-proof" lights or hand lamps.

14. The entry person must not remain in the confined space if he/she becomes even slightly drowsy, faint, dizzy, or otherwise uncomfortable. Many of the gases that cause the most problems are odorless, tasteless, and invisible.

CONFINED SPACE ENTRY CHECKLIST
GENERAL ENTRY

Site Name: ______________________ Entry Date: ______________________
Site Location: ______________________
Type of Confined Space: ______________________ Weather: (if applicable) ______________________
Work to be Performed: ______________________
Level of Personal Protection: ______________________

Potential Hazards: (Check all that apply)

☐ Corrosive	☐ Reactive	☐ Radioactive	☐ Hot Equipment
☐ Ignitable	☐ Volatiles	☐ Noise	☐ Falling Objects
☐ Toxic	☐ Biological	☐ Sharp Objects	☐ Pressure Systems
☐ Other: (list) ______			

Yes	No	N/A	
☐	☐	☐	Will work performed produce additional hazards (e.g. welding, cleaning, etc)? List: ______
☐	☐	☐	Were instruments calibrated prior to entry? More often if needed?
☐	☐	☐	Will atmosphere be monitored during entire entry?
☐	☐	☐	Was confined space ventilated prior to entry?
☐	☐	☐	Will ventilation continue during entry?
☐	☐	☐	Is air intake of the ventilation system located in an area free of exhaust and combustible/toxic substances?
☐	☐	☐	Has space been isolated from other systems?
☐	☐	☐	Has mechanical equipment been locked-out or disconnected?
☐	☐	☐	Has mechanical equipment been blocked, chocked, disengaged, and/or disconnected where necessary?
☐	☐	☐	Are safety lines and harnesses used?
☐	☐	☐	Will wrist-type harnesses be used if entryway is less than 18 in.?
☐	☐	☐	Are nonsparking tools and intrinsically safe/explosion-proof powered tools and lighting used?
☐	☐	☐	Is respiratory protection used? Type: ______

Entry Person(s): ______________________
Standby Person: ______________________ Rescue Person: ______________________
Other: ______________________
Prepared By: ______________________

SEND A COPY OF THE COMPLETED FORM TO THE HEALTH AND SAFETY SUPERVISOR

Figure A-2

Source: ABB-ES

Confined Space Entry Checklist: General Entry.

CONFINED SPACE ENTRY LOG

INITIAL ATMOSPHERE TESTING RESULTS: Record time and results of initial testing. If ventilation is necessary, record readings when the atmosphere stabilized and at 5-minute intervals.

	Breathing Zone	Initial	Atmosphere Stabilized	@ 5 min.	@ 10 min.
Time					
Combustible Gas Meter (%LEL)					
Oxygen Meter (%Oxygen)					
Hydrogen Sulfide Meter (ppm)					
PID Meter (ppm)					
Draeger Tube (ppm) Tube:					
Other List:					

ENTRY ATMOSPHERE TESTING RESULTS: Record time and the results of monitoring at initial entry and at 10-minute intervals. If no change in levels, extend to every 15 minutes. If significant fluctuations occur, reduce to every 5 minutes. (Note: Meters should be operated continuously in the confined space.)

	Initial				Final
Time					
Combustible Gas Meter (%LEL)					
Oxygen Meter (%Oxygen)					
Hydrogen Sulfide Meter (ppm)					
PID Meter (ppm)					
Draeger Tube (ppm) Tube:					
Other List:					

SEND A COPY OF THE COMPLETED FORM TO THE HEALTH AND SAFETY SUPERVISOR

Figure A-3

Source: ABB-ES

Confined Space Entry Checklist Worksheet.

Manhole/Sewer Entry

When preparing to enter a manhole/sewer, the following safety measures must be taken:

1. Inspect all pieces of equipment to ensure they are all in good working order. DO NOT ENTER CONFINED SPACE WITH DEFECTIVE EQUIPMENT.

2. Park the vehicle near the manhole (do NOT leave the vehicle running). If the manhole is in the street, it is best to park so as to detour oncoming traffic around the manhole. The vehicle's emergency flashers and portable yellow warning beacon must be ON. The vehicle serves as protection from oncoming traffic, can be used to store emergency equipment (e.g., SCBA and first aid kit), and can be used in an extreme emergency to slowly pull an injured person from the confined space if a tripod with hoist attachment is unavailable or inoperative.

3. Erect portable barricades or cones around the manhole and in front of the vehicle to divert traffic and prevent pedestrians from falling in. Reflective vests should be worn so that workers are visible to approaching traffic.

4. If there are openings large enough to admit sampling tubes, test for the presence of explosive and toxic gases before removing each manhole cover. Otherwise, raise one side of the cover using the cover hook or pick, prop it slightly open, and conduct the tests.

5. If toxic or explosive gases are detected in the sewer, report this immediately to the local fire department and/or department of public works.

6. Record the results of tests for hazardous conditions, including location, manhole number (if applicable), time and date, weather (if applicable), and the readings on the photoionization detector (PID), combustible gas meter, oxygen deficiency meter, and Draeger tube on the Manhole/Sewer Entry Log Form. Send a completed copy of the form to the HSS.

7. Remove manhole covers with a cover hook or pick; do not improvise. Be careful of fingers and toes; covers are usually heavy and difficult to handle. Unless the cover is extremely heavy, it is safer for only one worker to handle it.

8. Test the atmosphere; if toxic, flammable, or oxygen-deficient, ventilate the sewer. Depending on the hazard, ventilation can be accomplished in a variety of ways: for example (1) remove and vent the adjoining upstream and downstream manhole covers, as soon as possible, and well in advance of entering the manhole (high hazard); and (2) vent the manhole in which entry will occur (very low hazard). If a blower is used, it is desirable to establish a flow of air in the sewer, in one manhole and out another. Ensure that the air intake is well away

from automobile exhaust, and combustible and/or toxic atmospheres. Appropriate traffic control measures must be taken by barricading or otherwise marking the open manholes.

9. After ventilating, test for explosive and toxic gases and oxygen deficiency in the manhole at ground level and at the bottom; record results. If entering the sewer itself, make the same tests at the manholes at either end. If ventilation is necessary, monitor the atmosphere in the manhole while work progresses, or continue operation of the blower. Continuous monitoring (i.e., equipment ON during entire entry) is imperative because conditions within the sewer may change rapidly. Do not enter a manhole while there is an oxygen deficiency without a pressure-demand, air-supplied breathing apparatus. If the oxygen level is lower than 20.9 percent of background, caution must be taken because an IDLH atmosphere may exist.

10. When entering manholes or tanks, wear a hardhat, protective clothing, and, when required, appropriate respiratory protection and safety belt or harness with lifeline. If the manhole is less than 18 inches in diameter, a wrist-type harness must be used and special provisions made if air-supplied respirators are necessary. When working in manholes greater than 12 feet deep, in the sewer itself, or where potential exists for gases to appear unexpectedly, a 5-minute emergency egress air supply is required (unless the time required to don the emergency respirator is greater than what would be needed to exit the manhole).

11. At least one person (i.e., standby) must remain at the manhole at all times and must keep continuous contact with the person entering the sewer. Contact can be maintained by line of sight, listening for sounds, and the safety line and/or radio. The standby person must not enter the manhole unless another trained person is available to act as standby and has adequate respiratory and dermal protection available. (In most cases, respiratory protection will be an airline respirator or SCBA.) The standby/rescue person should be suited up (but not yet on air) before the work crew enters the confined space.

12. Do not smoke when working in or near manholes. Do not take flash-lighted photographs when explosive gases are known or suspected to be present.

13. Do not rely on the manhole ladders because they are often in poor condition. If they must be used, be sure of footing. Inspect manhole ladders for deterioration before entering and while descending. Try each step with one foot, while standing on the step above. When in doubt, use a portable ladder of adequate height to reach 3 feet above the manhole opening, or lower the entry person using the tripod. If a portable ladder is used, it should be tied off if possible; otherwise, it should be held in place by the standby person.

14. Do not work without adequate lighting. Use only "explosion-proof" lights or hand lamps in the manhole or sewer.

15. The entry person must not remain in the manhole or sewer if he/she becomes even slightly drowsy, faint, dizzy, or otherwise uncomfortable. Remember that carbon monoxide, carbon dioxide, methane, and hydrogen sulfide, which cause the most trouble, are odorless, tasteless, and invisible. Hydrogen sulfide has a distinct odor only during initial exposure.

MANHOLE/SEWER ENTRY LOG

Location:________________________________ Date:____________________
Crew Chief:______________________________ Others:____________________
HSO:____________________________________ ____________________

Two-way radio available and working?____________________________________
Traffic control equipment in place?____________________________________
Location of nearby emergency telephone:____________________________________
Ambulance________________ Fire Dept.____________ Police____________
Hospital________________ Agency____________________________
Level of personal protective equipment to use:____________________________
Safety harness with lifeline used?____________________________________
Monitoring equipment calibrated prior to use?____________________________
Monitoring equipment condition: Hydrogen Sulfide Meter:_______ PID:_______ Oxygen/LEL:_____
Other____

INITIAL ATMOSPHERE TESTING RESULTS

	Time	Hydrogen Sulfide	PID	Oxygen	LEL	Other
Manhole Opened						
Begin Ventilation						
Atmos. Stabilized						
Tv + 5 minutes						
Tv + 10 minutes						

Tv = Start of Ventilation

ENTRY ATMOSPHERE TESTING RESULTS

	Time	Hydrogen Sulfide	PID	Oxygen	LEL	Other
Entry						
Te + 10 minutes*						
Te + 20 minutes*						
Te + 30 minutes*						

Te = Time of entry * More often if needed

SEND A COPY OF THE COMPLETED FORM TO THE HEALTH AND SAFETY SUPERVISOR

Figure A-4

Manhole/Sewer Entry Log.

Source: ABB-ES

ATTACHMENT 2

HEALTH AND SAFETY AUDIT CHECKLIST

HEALTH AND SAFETY AUDIT CHECKLIST

Site Name ____________________________________ Date __________

GENERAL	YES	NO	COMMENTS
HASP on-site?	___	___	_______________
Completely signed off and approved?	___	___	_______________
Only employees listed and approved in HASP on-site?	___	___	_______________
All personnel properly trained?	___	___	_______________
All personnel in health monitoring?	___	___	_______________
Zones established?	___	___	_______________
Unusual situations on-site, not listed in HASP?	___	___	_______________

What?____

Action taken?____

Hasp revised?____

Are daily tool-box meetings held?	___	___	_______________
OSHA poster posted in trailer?	___	___	_______________
If night work is to be conducted, adequate illumination?	___	___	_______________
Proper sanitation facilities?	___	___	_______________

PERSONAL PROTECTIVE EQUIPMENT

Proper PPE being worn as specified in the HASP?	___	___	_______________
PPE adequate for work conditions?	___	___	_______________

If no, reason? ____

up/down grade to PPE level____________________________________

PERSONAL PROT. (cont.)	YES	NO	COMMENTS
Facial hair which would interfere with fit of respirators?	___	___	________________
If Level B, backup/emergency person suited up (except for air)?	___	___	________________
HSO periodically inspects PPE & equipment?	___	___	________________
PPE not in use properly stored?	___	___	________________
EMERGENCY RESPONSE			
Emergency response plan part of HASP?	___	___	________________
Emergency procedures discussed during tool-box meetings?	___	___	________________
Vehicle available on-site for transportation to the hospital?	___	___	________________
Fire extinguishers on-site?	___	___	________________
At least two persons trained in CPR and first aid on-site at all times?	___	___	________________
All personnel know who is trained?	___	___	________________
Emergency evacuation conducted?	___	___	________________
Reason____			
Level of evacuation:			
Withdrawal upwind	___	___	________________
Site evacuation	___	___	________________
Evacuation of surrounding area	___	___	________________
First-aid kit on-site?	___	___	________________
Adequately stocked?	___	___	________________
Inspected weekly?	___	___	________________

EMERGENCY RES. (cont.)	YES	NO	COMMENTS
Emergency eye-wash on-site?	___	___	______ ___
Emergency shower on-site?	___	___	________________
Stretcher on-site?	___	___	________________
Emergency numbers posted in trailer?	___	___	________________
DECONTAMINATION			
Decontamination line set up properly?	___	___	________________
Proper cleaning fluid used for known or suspected contaminants?	___	___	________________
Proper decontamination procedures used?	___	___	________________
Decontamination personnel wearing proper PPE?	___	___	_______________
Equipment decontaminated?	___	___	_______________
Disposable items changed at least daily and more often if needed?	___	___	________________
Proper collection and disposal of contaminated PPE?	___	___	________________
Proper collection and disposal of decontamination fluid?	___	___	________________
Water available for decontamination?	___	___	________________
MONITORING EQUIPMENT			
All equipment listed in HASP on-site?	___	___	________________
Properly calibrated?	___	___	________________
In good condition?	___	___	________________
Used properly?	___	___	________________
Other equipment needed?	___	___	________________

List____

Monitoring equipment covered with plastic to minimize contamination?	___	___	________________

WORK PRACTICES	YES	NO	COMMENTS
Buddy system used?	___	___	__________
Equipment kept off drums and ground?	___	___	___________
No kneeling or sitting on drums or ground?	___	___	___________
Personnel avoid standing or walking through puddles or stained soil?	___	___	____________
No smoking, eating, or drinking in the Exclusion Zone or CRZ?	___	___	____________
To the extent feasible, contaminated materials handled remotely?	___	___	_____________
No contact lenses allowed on-site?	___	___	_____________
No entry into excavations unless properly shored or sloped?	___	___	_____________

CONFINED SPACE ENTRY

All confined spaces identified?	___	___	_____________

If not, list____

All appropriate equipment available and in good working order?	___	___	_____________
Equipment properly calibrated?	___	___	_____________
Confined Space Checklists used?	___	___	______________
Checklists completely and correctly filled out?	___	___	______________

DOCUMENTATION AND RECORDKEEPING	YES	NO	COMMENTS
Daily field records kept by the Site Manager?	___	___	_______________
Site surveillance records kept by HSO?	___	___	_______________
Daily safety log kept by HSO?	___	___	_______________

____ ______________________________
Health and Safety Supervisor Date

____ ______________________________
Health and Safety Officer Date

PARAMETERS	CLASS A (LEVEL A OR B PPE)	CLASS B (LEVEL B OR C PPE)	CLASS C (LEVEL D PPE)
Characteristics	**IDLH: rescue procedures require the entry of more than one individual fully equipped with life-support equipment; maintenance of communication requires an additional standby person stationed within the confined space.	Dangerous, but not immediately life-threating: rescue procedures require the entry of no more than one individual fully equipped with life-support equipment; indirect visual or auditory communication with workers.	Potential hazard requiring no modification of work procedures: standard rescue procedures, direct communication with workers from outside the confined space.
Oxygen	19.4 percent or less *(122-mm Hg) or greater than 25 percent *(190-mm Hg).	19.5 to 21.4 percent *(122- to 147-mm Hg) or 21.5 to 25 percent (163- to 190-mm Hg).	19.5 to 21.4 percent *(148- to 163-mm Hg).
Flammability Characteristics	20-percent or greater LEL.	10- to 19-percent LEL.	10-percent LEL or less.
Toxicity	**IDLH.	Between the TLV/PEL and **IDLH. If air-purifying respirators are used, maximum level based on breakthrough time (1,000-ppm maximum).	Less than the TLV/PEL.
Respiratory Protection	SCBA or supplied-air respirator with escape bottle.	SCBA, supplied-air respirator with escape bottle or air-purifying respirator.	None.

* Based on total atmospheric pressure of 760-mm Hg (sea level).

** "Immediately Dangerous to Life or Health", as referenced in NIOSH Registry of Toxic and Chemical Substances, Manufacturing Chemists data sheets, industrial hygiene guides, or other recognized authorities.

NOTES: Hg = mercury; LEL = Lower Explosive Limit; PEL = Permissible Exposure Limit; PPE = Personal Protection Equipment; ppm = parts per million, SCBA = Self-contained Breathing Apparatus; TLV = Threshold Limit Value.

Source: ABB-ES

Table A-2

Confined Space Classification

APPENDIX B

EFFECTIVENESS OF PROTECTIVE MATERIALS AGAINST CHEMICAL DEGRADATION (BY GENERIC CLASS)

EFFECTIVENESS OF PROTECTIVE MATERIALS AGAINST
CHEMICAL DEGRADATION (BY GENERIC CLASS)[1]

Generic Class	Butyl rubber	Polyvinyl Chloride	Neoprene	Natural rubber
Alcohols	E	E	E	E
Aldehyde	E-G	G-F	E-G	E-F
Amines	E-F	G-F	E-G	G-F
Esters	G-F	P	G	F-P
Ethers	G-F	G	E-G	G-F
Fuels	F-P	G-P	E-G	F-P
Halogenated hydrocarbons	G-P	G-P	G-F	F-P
Hydrocarbons	F-P	F	G-F	F-P
Inorganic acids	G-F	E	E-G	F-P
Inorganic bases and salts	E	E	E	E
Ketones	E	P	G-F	E-F
Natural fats and oils	G-F	G	E-G	G-F
Organic acids	E	E	E	E

[1] E - Excellent F - Fair
G - Good P - Poor

Source: Survey of Personal Protective Clothing and Respiratory Apparatus. DOT, USGS, Office of Research and Development (September 1974).

APPENDIX C

RISK/HAZARD ANALYSIS CALCULATIONS

Threshold limit Value - Time Weighted Average: This calculation is used when determining the employee exposure over an 8-hour day.

$$TLV\text{-}TWA^{1} = \frac{(C_1 \times T_1) + (C_2 \times T_2) + \ldots + (Cn \times Tn)}{8 \text{ Hours}}$$

C = Concentration
T = Time (hours)

Cumulative Threshold Limit Value: This calculation is used when there is a mixture of chemicals in the air which have similar effects on the body (i.e., liver toxins). These chemicals will have an additive effect so the TLVs must be combined to determine the cumulative TLV.

$$\text{Cumulative } TLV^{1} = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{Cn}{Tn} \leq 1$$

C = Concentration
T = Time (hours)

(Note: If the results are over one, the cumulative TLV has been exceeded)

Henry's Law Constant: This calculation is used to estimate the maximum concentration of contaminant which can be found in the air under equilibrium conditions, based on the concentration found in the water.

$$\text{ppm(atmos.)} = \frac{\text{Conc. in water}}{MW} \times H \times 10^6$$

H = Henry's Law Constant in atm-m^3/mol
Conc. in water = mg/l
MW = Molecular Weight
10^6 = one million

Note: To calculate Henry's Law Constant

$$H = \frac{\text{Molecular Weight } (mg/m^3) \times \text{Vapor Pressure (mm Hg)}}{\text{Solubility in water} \times 760 \text{ mm Hg}}$$

Conversion of ppm to mg/m^3 (gases and vapors only): To convert from parts per million to milligram per cubic meter of airborne gases and vapors.

$$ppm = \frac{mg/m^3 \times 24.45}{MW}$$

1 After ACIGH, 1987

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 3.1 EXPLORATORY TEST PITS

SECTION 3.1
EXPLORATORY TEST PITS

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3.1 EXPLORATORY TEST PITS

3.1-1 PURPOSE

Test pits and trenches are excavated by backhoe equipment to provide detailed visual examination of near-surface soil, ground water, and bedrock conditions. The depth of excavation depends on site conditions and type of equipment used. The major advantages of test pits over soil borings are as follows:

- The near-surface stratigraphy is exposed, facilitating sample collection and recovery and logging of soil, water level, and bedrock surface.
- Information is provided on the lateral and vertical extent of subsurface features.
- Test pits are usually cost-effective over this depth, and equipment is readily available.

The size of the backhoe equipment and the procedures to be employed are influenced by the type of information to be obtained, anticipated level of contamination (if any), and depth of excavation required. Site-specific safety issues (i.e., test pit stability, contamination potential, and impacts on ground water) should be considered when designing a test pit program. Installation of observation wells in test pits is not recommended; if installed, they should be used for water level data only, not water quality sampling.

3.1-2 METHODOLOGY

The following sections summarize the methodology for test pit explorations, including excavation, hazardous waste protocols, logging and sampling, and backfilling.

3.1-2.1 Excavation

Prior to the start of the test pit program, all potential test pit locations should be laid out to the nearest foot. The presence or absence of underground utilities should be determined before excavation begins. DIG-SAFE should be contacted to clear utilities within a public right-of-way (1-800-DIG-SAFE). All utility companies with potential underground services should be contacted; approval by their representatives should be secured prior to excavation at individual test pit locations. In urban areas, this may require obtaining permits from the city or town of jurisdiction.

The sampler and backhoe operator should plan each test pit excavation. The backhoe operator should excavate the test pit in several increments of depth. After each increment, the operator should wait while the sampler inspects the test pit to decide if conditions are appropriate for sampling. Practical depth increments generally range from 1 to 4 feet. The backhoe operator, who will have the best view of the test pit, should cease digging if any of the following conditions are encountered:

- o Distinct changes in stratigraphy or materials.
- o Odors.
- o Ground water or fluid-phase contaminants.
- o Drums or other potential waste containers.
- o Utility lines not previously identified.

These actions are necessary to permit proper logging and sampling of the test pit, and to prevent a breach in safety protocol. For example, if seepage or fluids are encountered, they could be sampled after suitable screening and monitoring. Waste and sludge deposits could likewise be sampled before proceeding. If uncollapsed drums are encountered, extreme caution must be exercised. The test pit should be terminated, an expert in drum removal should be engaged, and a new test pit should be dug at an adjacent location.

3.1-2.2 Hazardous Waste Protocols and In-pit Safety

To expedite sampling and recordkeeping efforts, and to minimize periods of potential exposure during test pit excavation, the sampling crew should have sufficient tools and equipment to sample each pit thoroughly without requiring decontamination. The backhoe and tools should be decontaminated between excavation of each test pit. Decontamination procedures described in Section 3.3 are appropriate for backhoe equipment. The backhoe bucket and boom should be decontaminated as required before excavation of each test pit at a central staging location. If necessary, decontamination wash water should be collected and stored on-site.

The actual area of each test pit, temporary staging area, and spoils pile will be predicated on site conditions and wind direction at the time the test pit is made. Contaminated spoils should be segregated from clean spoils during stockpiling.

The preselection and use of hand and horn signals is important during completion of test pits due to noise levels around the backhoe. The sampling crew and backhoe operator should rehearse appropriate signals ahead of time and be thoroughly familiar with their meanings. All personnel should be equipped with air-blast horn devices, especially when wearing respiratory safety gear, which hinders communication.

During test pitting, an organic volatile analyzer must continuously monitor for any releases to the environment in the work area and at the facility boundary, as appropriate. Sampling and logging should be done from the ground near the test pit surface unless levels of organics, explosive gases, and oxygen are within acceptable limits. These levels should be measured in the field using field-screening equipment.

Under no circumstances should an individual enter a test pit deeper than 5 feet unless side slopes have been cut back to acceptable Occupational Safety and Health Administration (OSHA) standards, and an experienced geologist or engineer has determined the pit safe to enter. Material excavated from the pit should be piled far enough from the edge of the excavation so that pit stability will not be influenced by the weight of this surcharge.

At potentially hazardous waste sites, the individual entering the test pit should be equipped with safety gear as required by the conditions in the pit, usually Level B. The individual should be affixed to a safety rope and continuously monitored while in the pit by a second individual at ground surface. The second individual should be fully dressed in protective clothing (including a self-contained breathing device) and standing by during all pit entry operations. The individual entering the pit should remain for as brief a period as practical. Further details on this subject are described in Section 2.3, Health and Safety Plans.

Sampling of unopened buried drums is excluded from these exploratory test pit protocols. Such work should be undertaken on a site-specific basis utilizing appropriate safety and sampling protocols for each instance.

3.1-2.3 Logging and Sampling Procedures

3.1-2.3.1 Logging

Features exposed in the test pits should be logged as they are excavated. Records of each test pit should be made on prepared forms or in a field notebook. If the log is made in a fieldbook, it should be transcribed to a prepared form. The records should contain plan and profile sketches of the test pit showing materials encountered, their depth and distribution, and, if necessary, sample locations. Two examples of test pit record forms are shown in Figures 3.1-1 and 3.1-2. These forms provide for entry of necessary sampling, monitoring, and subsurface data for each test pit in a concise and uniform manner, and provide a cross-check with chain-of-custody records and sample label counts. If hazardous materials are anticipated or encountered, the records should also include safety and screening information.

If necessary, a grid system should be used on the face of the test pit to facilitate the measurement and distribution of strata and samples. Soils and rock should be classified in accordance with procedures outlined in Sections 3.5 and 3.7. At a minimum, the test pit log should include the following information:

- Plan and profile sketches of the test pit showing materials encountered, the depth and distribution of these materials in the test pit, and sample location.

- Sketch of the test pit location showing permanent and identifiable location marks.

- Photographs of test pit walls or excavated material.

- The size, quantity, and type of boulders and fill materials excavated from the pit.

- Representative samples, as required.

- The presence or absence of ground water or surface water entering the pit, and a record of the approximate rate of flow.

- The nature and character of bedrock, including attitudes of bedding and discontinuities, as well as relative structural features (a supplemental sketch may be of value).

- A record of voids, stability, and density of the materials encountered, and obstructions to excavation.

- Torvane and/or pocket penetrometer readings, which should be obtained as field measurements of shear strength where cohesive soils are encountered.

- Safety and screening information, if hazardous materials are anticipated or encountered.

- Notation of reason for terminating the test pit.

3.1-2.3.2 Sampling

The actual depth and type of samples to be collected from each test pit should be selected prior to the initiation of the test pit program, if sufficient information exists, or at the time of test pit excavation. Sufficient samples should be obtained to adequately characterize the soil stratigraphy through laboratory index testing (i.e., moisture content, organic content, grain-size distribution, hydrometer analysis, and Atterberg limits). If hazardous materials are anticipated or encountered, the sampling should be sufficient to adequately characterize the contaminant distribution as a function of depth for each test pit. Additional samples of each waste phase and any fluids encountered in each test pit may be collected. Due to uncontrolled exposure to the atmosphere, samples collected from test pits will not be suitable for analysis of volatile organic compounds.

To sample a pit two methods can be used:

- o Samples are withdrawn from the test pit using the backhoe bucket.
- o Samples are obtained from within the test pit.

The method to be used should be selected in the field at the time the test pit is sampled.

(a) <u>Samples of Soil and Fluids Obtained from the Backhoe Bucket</u> The sampler or crew chief should direct the backhoe operator to remove material from the selected depth or location within the test pit. The bucket should be brought to the surface and moved away from the pit edge. If hazardous substances are encountered, the sampler should approach the bucket and monitor its contents with a photoionization meter. If granular or loose soils and/or uniform materials are encountered, a sample can be obtained directly from the bucket. The sample should be collected from the center of the bucket and placed in sample jars using a clean, decontaminated trowel or spatula.

If cohesive or multiphase conditions are encountered (i.e., the bucket contains a mixture of granular soil and cohesive soil or sludge), the sampler should proceed as above, if practical. If not, the sampler should direct the backhoe operator to empty the bucket on the ground. Samples should be obtained from the interior of soil clods or lumps of cohesive soils or sludge using a clean trowel or spatula.

(b) <u>Samples Obtained from Within the Test Pit</u>. Samples can be obtained directly from the test pit providing it is safe to enter. This sample procedure may be necessary when soil conditions preclude obtaining suitable samples from the backhoe bucket (e.g., caving or excessive mixing of soils or wastes within the test pit, or when samples from relatively small discrete zones within the test pit are required). This method may also be required to sample seepage occurring at discrete levels or zones within the test pit. Under these circumstances, samples should be obtained with extendable-handle tools: scrapers, trowels, spoons, or cups. The face of the test pit should be scraped to remove the smeared zone that has contacted the backhoe bucket. The material to be sampled (if a solid) should then be removed from the test pit wall by clean, long-handled scoops or trowels, and placed in sample jars.

If a composite sample is required, several depths or locations within the pit should be selected, and a stainless steel bucket should be filled from each area. A soil sample of known volume should be obtained from each bucket, emptied onto a mixing surface (e.g., stainless steel pan or plastic sheet), and thoroughly mixed before being placed in sample jars. The mixing surface should then be decontaminated or discarded; the spoils should be backfilled in the test pit.

3.1-2.4 Backfilling

A test pit should be backfilled immediately after its completion. The backfilling should be performed in maximum 18-inch lifts, and bucket-tamped or track-rolled by the equipment. No test pit should ever be left open overnight when a site is unattended.

Upon completion of the test pit, the excavated materials should be replaced in more or less the same stratigraphic order. If highly contaminated soil were encountered at or near the surface, they should be replaced near the surface with a clean soil cover. In cases where gross contamination by hazardous materials is encountered at an otherwise uncontaminated location it is safer and more cost-effective to segregate the grossly contaminated soil for off-site disposal and fill the test pit with clean, uncontaminated soil. During sampling and logging of each pit, the backhoe operator and all nearby site personnel should remain upwind or crosswind of the test pit and spoils pile. Wind direction should be monitored by a windsock or other banner located in a prominent position visible to all personnel.

3.1-3 EQUIPMENT NEEDED

- personal protection equipment and clothing
- excavator (size and type dependent on depth and accessibility)
- hand shovel
- 100-foot cloth tape
- 6-foot rule
- pocket penetrometer and torvane
- bags and/or 5-gallon pails with labels
- stakes and flagging
- camera
- indelible pen
- site plans and forms
- pumps (if dewatering is necessary)
- compaction equipment (if required for backfilling purposes)

- decontamination equipment for excavator and sampling equipment (if hazardous materials are anticipated)

- clean backfill if necessary

- PVC sheeting

REFERENCES

Occupational Safety and Health Administration (undated), OSHA manual for soil and foundation engineering firms: Silver Spring, Maryland, Reprinted by Association of Soil and Foundation Engineers, 612 p.

ADDITIONAL REFERENCES

Hvorslev, M.J., 1949, Subsurface exploration and sampling of soils for civil engineering purposes: Vicksburg, Mississippi, U.S. Army Engineer Waterways Experiment Station, 521 p.

U.S. Department of the Army, 1972, Soil sampling: Washington, D.C., Engineer Manual EM 1110-2-1907, various pages.

SECTION 3.1 EXPLORATORY TEST PITS

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TEST PIT RECORD

Page 1 of 2

SITE ____________________

TEST PIT ____________ DATE ____________ TIME ____________ END ____________

COORDINATES ____________ GRID ELEMENT ____________

SKETCH MAP OF TEST PIT SITE
(SHOW SURFACE MONITORING RESULTS)

N

WIND

SCALE 1" = ____________ FT.

NOTES: ____________________

CREW MEMBERS:

1.

2.

3.

4.

5.

6.

MONITOR EQUIPMENT:

PI Meter	Y	N
Explosive Gas	Y	N
Avail. Oxygen	Y	N
OVA	Y	N

Other ____________

Photographs, Roll ____________

Exposure ____________

Figure 3.1-1

Example of Test Pit Record.

Source: ABB-ES

TEST PIT RECORD

Page 2 of 2

Profile Along Test Pit- ____________________

SITE ____________________

TEST PIT DATE __________ TIME ________ END COORDINATES ________ GRID ELEMENT ________

SKETCH OF TEST PIT CROSS SECTION
(SHOW SURFACE MONITORING RESULTS)

SCALE 1" = __________ FT.
DEPTH (FT.)

NOTES: ____________________

SAMPLES OBTAINED:

No.	Depth (Ft.)	Sample ID	PI Reading
S-1			
S-2			
S-3			
S-4			
S-5			
S-6			
S-7			
S-8			

REFERENCE: Field Book, Pg. __________

Attachments __________

SIGNATURE: ____________________

Figure 3.1-1
(Continued)
Example of Test Pit Record.

Source: ABB-ES

LOG OF TEST PIT No.

January 1991

Test Pit Dimensions:	Face of Test Pit Logged:	Date Excavated	Project No.	Sheet No.

Depth to Water:	Estimated Stripping Depth:	Logged By:

Surface Elevation:	Surface Conditions:

DEPTH (FEET)	SAMPLE NO.	LAB TEST	WATER CONTENT (%)	SOIL CLASS.	DESCRIPTION	ELEVATION (FEET)	REMARKS
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							

Groundwater

Date	Time*	Depth/Ft.
Not Encounted		Hrs. after Compl.

_____ X _____ X _____ = _____ Cu. Ft.
(L) (W) (D)

8" to 18" Diam: No._____ "Vol._____ Cu. Ft.
Over 18" Diam: No._____ "Vol._____ Cu. Ft.

Summary

Depth _____
Jar Samples _____
Bag Samples _____
Groundwater _____
Test Pit No.

Figure 3.1-2

Source: ABB-ES

Example of Test Pit Report

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STANDARD REFERENCES FOR MONITORING WELLS

SECTION 3.2 DRILLING TECHNIQUES

SECTION 3.2
DRILLING TECHNIQUES

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SECTION 3.2

DRILLING TECHNIQUES

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Section 3.2 DRILLING TECHNIQUE

3.2-1 PURPOSE

Prior to selecting the drilling technique for a specific project, the objectives of the field investigation program must be established. The program objectives may include any or all of the following:

- Soil or rock evaluation - if undisturbed or representative samples are required, the drilling technique must be able to accommodate the appropriate type of sample collection.

- Characterization of hydrogeologic conditions - the drilling technique should allow for the characterization of each stratigraphic zone, water level measurements, and water sample collection.

- Evaluation of soil or ground water contamination - the drilling technique must provide the appropriate sample collection methods, must not introduce contaminants into the borehole or otherwise alter the existing soil or groundwater chemistry, and should not result in subsurface cross-contamination during or after drilling.

- o Installation of monitoring wells - the drilling method must permit appropriate well construction and minimize the disturbance to both the borehole and the well.

Choice of a specific drilling technique for an investigation will impact the schedule, cost, and technical quality of a field investigation. The quality and representativeness of the soil and ground water samples can be significantly affected by the drilling technique employed. Several items must be taken into consideration to determine the most appropriate drilling method. One of the best resources for selecting an appropriate drilling technique is an experienced drilling contractor. Items that should be considered in the selection process include the following:

o <u>Geologic Conditions</u>:

- unconsolidated or consolidated
- ype of material, including fill material
- presence of boulders or cobbles
- depth to bedrock

o <u>Site Access</u>:

- property ownership
- terrain and vegetative cover
- wet areas
- size of the working area
- weather conditions
- weight and size restrictions

- need for barge equipment
- location of drilling water source

o <u>Seasonal Conditions Affecting Access</u>:

- effect of freezing temperatures, mud, and snow on drilling progress
- use of water
- need to add antifreeze to pumps when not in use under freezing conditions
- antifreeze must be flushed out of hoses and pumps
- high water conditions

o <u>Existence of Contamination</u>:

- utilize decontamination protocols
- minimize disturbance and cross-contamination
- minimize impact on site chemistry
- control drilling discharge
- reduce volume of contaminated spoils
- sampling requirements
- minimize crew's exposure to hazards

- follow appropriate health and safety procedures (See Section 2.3 Health and Safety Plans for more information).

o <u>Required Hole Size and Plumbness</u>:

- single-level or multiple-level well installations (See Section 4.0 Piezometers, Observation Wells and Monitoring Wells)
- large-diameter wells
- installation of instruments and downhole equipment
- availability of drilling equipment
- adequate annular space for well installation
- use of packers

o <u>Drilling Rates</u>: DEP projects are almost always conducted on a per diem (time and materials) basis; outside consultants may find it to their advantage to contract the services of a driller on another cost basis (i.e., unit price per foot of soil or rock drilled).

Cost, drilling rates, or availability of equipment should not be the determining factors in choosing a drilling technique. An evaluation should be made of the impact of the drilling method on the integrity of the subsurface soil and ground water samples to be obtained in the investigation. Costs for chemical analyses are high, and money should not be wasted on analysis of unrepresentative samples. Also, analyses and remediation based on faulty data from improperly drilled wells could ultimately be quite costly, greatly exceeding the cost of a well-conceived field investigation program.

Several drilling techniques that are commonly employed in environmental investigations are described in the following subsections. The basic drilling technique is described, along with its advantages and disadvantages, for the following methods:

o Cable Tool
o Drive and Wash
o Spun Casing
o Solid Stem Augers
o Hollow Stem Augers
o Mud Rotary
o Air Rotary/Air Hammer
o ODEX System

Included in Tables 3.2-1 through 3.2-8 and Appendix A is some useful information on standard casing diameters, casing volumes, drill bits and terminology.

3.2-2 CABLE TOOL

3.2-2.1 General Considerations

The cable tool method is a percussion drilling method; it employs a drill bit, attached to a heavy string of drilling tools, that is repeatedly pounded against the bottom of the hole to break up the rock or soil formation into small fragments. Table 3.2-2 shows dimension and weights for standard cable tool drill bits in English and SI units. Water is added to the borehole to form a slurry of the broken rock and soil fragments.

Periodically this slurry is removed from the borehole using a bailer or sand pump. A bail handle at the top of this tool attaches to a cable called the sand line. The sand line is threaded over a separate sheave at the top of the mast and down to the line reel. The diameter of the sand line can vary according to the anticipated loads (Driscoll, 1986).

In unconsolidated or deep borings, the hole is often cased with thick-walled steel casing to prevent collapse of the sidewalls. Casing diameters for the cable tool method generally range from 4 to 24 inches although larger holes can be drilled. Depending on the purpose of the borehole, the drive casing may be removed from the ground or left in place. Figure 3.2-1 is a diagram of a typical cable tool setup. Figure 3.2-2 illustrate equipment used in the cable tool drilling method.

The cable tool method can be used in most soil and rock conditions. In environmental investigations, the cable tool method is generally employed when other methods are undesirable due to their impact on the in-situ chemistry and permeability, or because adequate penetration cannot be achieved with other methods. The cable tool drilling method is suitable for coarse, dense soils such as boulder tills and boulder-cobble-rich, ice-contact deposits. Additionally, the cable tool method is particularly suitable for drilling in highly fractured or cavernous rock formations, and fill debris.

Soil samples can be collected in a variety of ways using the cable tool method. Typically, samples of the bailed slurry are obtained and described. With some minor retrofitting, split-spoon samples can be obtained from the borehole, although this slows the drilling process considerably. Generally, good quality monitoring well installations can be completed in cable tool borings, although, compared with other methods, more time is required to install monitoring wells with the cable tool method.

3.2-2.2 Drilling Methodology

3.2-2.2.1 Drilling Action

The drilling action of the cable tool rig consists of an up-and-down motion of the drilling tools, at a rate controlled by the driller. The vertical stroke of the drill tools can be adjusted by changing the position of the pitman pin [see Figure 3.2-1]. Several factors affect the rate of penetration including the nature of the formation, depth to the water table, and the skill of the driller.

3.2-2.2.2 Driving Casing

When drilling soft or unconsolidated formations, casing must be used to keep the borehole open. A hardened steel drive shoe must be attached to the bottom of the casing to prevent breaking or damage to the casing during penetration. A drive head is placed on top of the casing to protect it from damage. Generally, the casing is driven into the ground with the drill tools. A drive block or clamp is attached to the drill tools and acts as a hammer face. The drill tools are lifted up and down; the pounding of the tools drives the casing into the ground.

Generally, the casing is driven for a distance of 3 to 10 feet without stopping. The disturbed material is then mixed with water, if necessary, to form a slurry; the slurry is bailed out of the casing. The driving, drilling, and bailing operations are repeated until the casing has reached the desired depth. If the subsurface materials are especially dense, the hole may be advanced 2 to 6 feet ahead of the casing to make the casing installation faster and to reduce the chance of casing breakage. The decision to pre-drill in advance of the casing should be based on the driller's judgement.

Depending on the nature of the boring, the casing may or may not be removed from the borehole upon completion. If required, the casing may be pounded back out of the ground by pulling back on the drive head. If the rig is outfitted with hydraulic jacks rather than a cathead arrangement, the casing can be removed more quickly and reliably.

3.2-2.2.3 Removal and Inspection of Cuttings

Formation cuttings are removed from the borehole with either a bailer or a sand pump. A bailer consists of a metal pipe with a check valve in the bottom. The bailer is lowered to the bottom of the borehole, the slurry enters the pipe, and when the bailer is lifted out of the hole, the check valve closes and the slurry is bailed out of the hole.

Alternatively, the cuttings can be removed from the hole with a sand pump or suction bailer. This method is similar to a check-valve bailer except that an internal plunger produces a vacuum that opens the valve when the bailer is lifted from the hole, sucking sand or slurried cuttings into the pipe. Some sand pump bailers have a latch bottom for slurry release. Bailers and sand pumps are generally 10 or 20 feet in length (Driscoll, 1986).

3.2-2.2.4 Telescoping Casing

If the borehole penetration slows considerably due to friction on the casing, it may be advisable to telescope to a smaller diameter casing. A second, smaller diameter casing string is inserted inside the first casing and drilling continues, resulting in a smaller diameter boring. In some cases, the casing size may have to be reduced two or three times in order to complete the boring to the desired depth. If telescoping of casing is expected, the initial casing size must be large enough to allow insertion of additional casings and still maintain the minimum size borehole desired.

3.2-2.3 Field Notes

In addition to the standard field notes such as who, what, when, and where, items that should be noted during the advancement of a cable tool boring include the following:

- total casing in the borehole
- depth of water-bearing horizons
- amount of water added to the borehole
- drilling rate per casing length and/or per foot
- description of formation material

- o sample type and depth interval

3.2-2.4 Advantages and Disadvantages

3.2-2.4.1 Advantages

- o Often the best method for penetrating dense, coarse soils, cavernous or fractured rock, and thick, permeable, unsaturated zones.
- o Rigs are relatively simple to operate and can generally be operated all year round.
- o Clean, relatively undisturbed borehole walls are produced.
- o Installation of casing assures that the borehole will remain open.
- o Excellent for gravel- or filter-packed wells.
- o Cased boreholes can be telescoped through contaminated zones to reduce the possibility of cross-contamination down the borehole.
- o Relatively small amounts of water that are not under pressure are required, reducing the impact of drilling water on aquifer water quality.
- o Suitable for deep boreholes (300 to 500 feet).
- o Large-diameter borings are possible (24 inches and greater).

3.2-2.4.2 Disadvantages

- o Drilling rate is slow to extremely slow (50 to 10 feet/day).
- o Disturbed soil samples are obtained with bailer or sand pump.
- o Casing removal may be slow and is not always successful.
- o Minimum borehole diameter relatively large (4 inches).
- o Difficult to identify the water table.
- o Availability of rigs and trained operators is limited.
- o Cannot recover intact rock cores.

3.2-2.5 Problems and Possible Solutions

3.2-2.5.1 Casing Broken Off Below Ground

As with any drilling method that uses casing, the potential exists for the casing to break off below the ground surface. Using a steel drive shoe and thick-walled casing will help to prevent this from happening. If the formation is especially dense, it is advisable to pre-drill ahead of the casing several feet to reduce the resistance to the casing. If the casing is broken, it may be possible to continue the boring by installing a smaller diameter casing in the hole. Any change in the original planned drilling method requires approval from DEP. In some instances, the boring may have to be abandoned when the casing is broken.

3.2-3.5.2 Slow Penetration

Although it is simple and reliable, the cable tool drilling method is inherently slow. At sites with substantial thicknesses of unsaturated materials, the frictional resistance on the casing may greatly impede drilling progress. In this situation, it is advisable to telescope to a smaller diameter casing to increase the rate of penetration.

3.2-3 DRIVE AND WASH

3.2-3.1 General Considerations

The drive and wash method (sometimes called wash and drive) requires the use of steel casing to maintain an open hole during drilling and sampling operations. The drive and wash method entails driving a casing into the ground with a 300-pound or heavier hammer dropped a specific distance, then after each interval, washing the soil cuttings out of the casing with a tricone or chopping bit and water. This method requires a nearby source of clean water or a water tank that must be brought to the boring site. Thin-wall, flush-joint casing ranging from 2.5 to 8 inches inside diameter (ID) in 5-foot lengths are typically used with this method. A hardened steel drive shoe is placed on the bottom of the lead casing to aid in penetration and to prevent the casing from splitting and breaking when rocks and cobbles are encountered. Representative soil samples can be collected with standard split-spoon samplers or tube samplers driven ahead of the casing. Figure 3.2-3 is a schematic of a typical drive and wash tool setup.

When conditions are appropriate, the drive and wash method is the preferred drilling method for monitoring well installation. This method is appropriate for many geologic conditions: sandy till and clay deposits; most sand and gravel conditions; organic soils; and fill materials. Because the casing is driven rather than spun, the drive and wash method results in less potential for cross-contamination. Recent studies by the U.S. Geological Survey (USGS) on Cape Cod, Massachusetts, indicate that the drive and wash methods produces a minimum amount of borehole disturbance compared to augers and rotary methods (Morin, 1988).

Also, because the bit is maintained inside the casing throughout the cutting removal process, there is a no jetting of the borehole sidewalls and, generally, the borehole maintains a consistent diameter. Under certain circumstances, such as dense tills, drilling ahead of the casing is permitted. The ease of casing removal and the similarity between the casing ID and the borehole ID allow for good quality and accurately placed well screen, filter pack and seals.

3.2-3.2 Drilling Methodology

3.2-3.2.1 Drilling Operation

A hardened steel drive shoe is typically placed on the bottom of the lead casing. The casing is driven into place using a manually controlled 300-pound or greater hammer or an automatic hammer system. At the discretion of the site geologist or engineer, blows counts may be recorded for discrete intervals of casing penetration. Changes in strata may be detected by changes in number of casing blows per foot, especially in shallow borings.

Once the casing length is driven to the desired depth, the drive head is removed and drill rods with a tricone or rotary bit are placed inside the casing. Table 3.2-3 presents the sizes and weights for standard tricone roller bits. The bit and rods are measured prior to placement in the hole. After the bit is placed inside the casing, the rod stick-up should be measured to determine the depth of the bit. The drill rod should then be marked at the point where the bit will be at the base of the casing. This marking procedure will prevent accidentally drilling below the casing, and disturbing material to be sampled.

3.2-3.2.2 Removal and Inspection of Cuttings

Only uncontaminated water must be used during the washing operation. It is important that this source be identified before the start of drilling and that prior approval be obtained from DEP.
Drill water is forced down through the drill rods to the bit to carry the cuttings up and out of the boring. It is imperative that the water ports in the cutting bit jet water out of the side of the bit and not ahead of the bit as this causes disturbance of the soil below the casing. A minimal amount of water necessary to carry the cuttings up and out of the hole should be used. The water level should be maintained at the top of the casing during the drilling operation, particularly when "running sands" are encountered. Recirculation of drilling water is permitted if the boring is not contaminated. Table 3.2-4 shows water volume for casings and holes of different diameters and depths. Table 3.2-5 presents standard size data for casings and drilling tools. Table 3.2-6 presents recommended rotating speeds and bit size for various formations.

Once the washing procedure is complete, the rods and bit are removed while maintaining the water level at the top of the casing. This should be done slowly to prevent "blowing in" of the formation. If required, a sample can be collected at this point. (See Section 3.4 for proper soil sample collection methods.)

Following sample collection or the washing out of the casing, an additional length of casing is added and the driving process continued.

3.2-3.3 Advantages and Disadvantages

3.2-3.3.1 Advantages

- An open borehole during drilling is assured because of the presence of the casing.
- Clean, relatively undisturbed borehole walls are produced.
- Method allows for inspection of the cuttings throughout the washing process.
- Inspection of cuttings allows for identification of geologic changes.
- Method allows for installation of monitoring wells inside casing.
- In-situ horizontal and vertical hydraulic conductivity measurements can be made.
- Method allows for collection of split-spoon or similar representative samples.
- It is a superior method for monitoring well installation.

3.2-3.3.2 Disadvantages

- A substantial source of water is required and a drilling water discharge is produced when water cannot be recirculated. If the borehole or ground water is contaminated, the discharge may require special treatment or collection procedures.
- The method is relatively slow; footage rates of 30 to 60 feet per day are common in New England soils.
- The water table and water-bearing zones may be difficult to recognize due to the addition of water into the system during drilling.
- Water circulation may be difficult to maintain in highly permeable, unsaturated soils.
- The addition of water to the aquifer system may be undesirable in some situations where contamination is present.
- This method is difficult for very coarse sands and gravels and cobbles and boulders.
- There is a very slight potential for cross-contamination due to flow along the outside of the casing.

3.2-3.4 Problems and Possible Solutions

3.2-3.4.1 Difficulty Removing Cuttings

Large, gravel-size particles may be difficult to wash out of the casing, especially as the borehole becomes deeper. Potential remedies for this problem include the following:

(a) Checking to see if drilling bits are in good condition and working properly.

(b) Using larger diameter drill rods. Small diameter (AW) drill rods in NW- or HW-size casing create a large annular space, decreasing the flow velocity up the annular space. Larger-diameter, heavier, gravel-size particles may not remain in suspension under these conditions. Switching to larger-diameter drill rods may solve this problem.

(c) Checking to see that the water pump on the drill rig is working properly and has sufficient capacity.

(d) In certain cases, the use of drilling mud or other additives to increase the density and viscosity of the drilling fluid will keep larger particles in suspension, carrying them out the hole. Drill-fluid additives should not be used when installing piezometers or monitoring wells where water quality or aquifer test results would be influenced by the additives. The use of drilling mud or other additives must be fully documented by the driller, included on the boring log, and described in the consultant's report.

3.2-3.4.2 Sand or Silt Flowing Up Inside the Casing -"Running Sands"

Sands or silts are often found to flow up inside the casing during the sampling or clean-out process. Unless true artesian ground water conditions are encountered within a stratum, this situation is usually the result of an unbalanced hydrostatic head between the borehole and the equivalent hydrostatic head in the formation at the elevation of the bottom of the casing. The imbalance occurs when drill rods are removed from the borehole, lowering the water level in the casing. This condition is usually associated with sand and/or silty soils where the unbalanced head creates a "quick" condition in the soil. If this condition, called "running sand," is encountered, it should be noted on the boring log because significant sample disturbance below the borehole often occurs. One possible way to minimize this problem is to remove the drill rods very slowly while concurrently adding water to the casing, thus maintaining the water volume displaced by the drill rods. This procedure maintains the water volume displaced by the drill rods. If this does not work, one may consider driving the casing past the zone of loose material into a more stable formation. The addition of non-aquifer water to minimize soil instability at the bottom of the casing should be fully documented by the drillers, included on the boring logs and described in the consultant's report. Furthermore, they must be able to document the fact that all non-aquifer water was removed during well development prior to collecting a sample for water quality analysis.

3.2-3.4.3 Loss of Drilling Fluid

Circulation return through the top of the borehole may cease if highly permeable formations are encountered at depth. In this situation the loss of fluid through the bottom of the casing is greater than the drill rig pumping rate. Three potential means are available to overcome this problem:

(a) Increasing the viscosity and weight of the drilling fluid with additives, as long as these additives will not influence the results of analytical testing of monitoring wells or the natural permeability in the vicinity of wells. Prior approval from DEP is required before using additives in the drilling operation.

(b) Cleaning out the casing without circulation return: this process involves breaking down the larger-size soil particles into sands and silt-size particles. The formation may have large enough voids to allow passage of the smaller-size particles out the bottom of the casing. This method should be used with caution because it is possible to jam the cutting tools in the casing with drill cuttings. It can be argued that sample recovery in zones of high hydraulic conductivity would be difficult due to the probable size of the soil particles or size limitations of the sampling tools.

(c) Driving past the sample interval to the next interval which may have a lower hydraulic conductivity. When this is done, it should be fully documented by the driller and included as a statement in the consultant's report.

3.2-4 SPUN CASING

3.2-4.1 General Considerations

Spinning casing is used as an alternative to typical drive and wash methods in conditions where a driven cased hole is unsuitable. This method is suitable for drilling soils and seating casing into bedrock. It is typically used in dense or boulder-rich strata such as lodgement till. In the spun casing method, a diamond spinning shoe or bit is attached to the bottom of the casing. The casing is attached to the drill head and advanced by a rotation and cutting action similar to coring. Water is forced down through the center of the casing and flows out and up the sides of the borehole, carrying cuttings to the surface. Residual soil material may remain inside the casing and must be cleaned out periodically with a rotary bit during advancement of the boring.

Two and a half- to eight-inch diameter, flush-joint casing in 5-foot lengths are typically used with this method. As with drive and wash methods, good-quality, representative tube and split-spoon samples can be obtained. Drill rigs capable of spinning casing include truck- and track-mounted types; both types are able to access most terrains. In general, good-quality well installations can be completed in spun cased holes, although large voids may develop along the borehole walls where the fines have been washed away by the water. The principal disadvantage of the spun casing method is that substantial amounts of drilling water may be lost into highly permeable formations during drilling. Thus a high potential for cross-contamination exists.

3.2-4.2 Drilling Methodology

3.2-4.2.1 Drilling Operation

A diamond spinning shoe or bit is placed on the bottom of the lead casing. The casing is attached to the drill head with a threaded adaptor. As the casing is spun and advanced, a slight downward pressure is applied. At the same time, water is pumped down through the rods, out the end of the bit, and up the annular space between the casing and the boring (Figure 3.2-4). If recirculation or collection of the drill water is necessary a larger diameter casing can be placed around the spun casing.

3.2-4.2.2 Removal and Inspection of Cuttings

Once the casing has reached the required depth, the distance to the bottom of the casing should be measured to determine if any cuttings remain inside the bottom of the casing. If there is material inside the casing, it should be removed by washing out prior to sampling. The drill rod attached to the bit should be marked where the bit reaches the bottom of the casing. This marking procedure will prevent accidentally washing beyond the bottom of the casing and disturbing the material to be sampled. Soil cuttings are carried to the surface with the water and this drill water is discharged at the top of casing, preferably to a recirculation tank equipped with a baffle to enhance settling of solids. When the boring is free of cuttings to the bottom of the casing, a sample may be collected.

Once the soil sampling process is completed, an additional length of casing is added, and drilling can continue.

3.2-4.3 Advantages and Disadvantages

3.2-4.3.1 Advantages

- Casing can be advanced through large-diameter cobbles and boulders.
- Drilling method is relatively rapid through large-diameter cobbles typical of many New England glacial tills.
- Representative samples can be obtained.
- Angle hole drilling is possible.
- Able to seat casing into bedrock to accommodate rock coring.
- Method allows for installation of monitoring wells inside the casing.

3.2-4.3.2 Disadvantages

- A continuous water source is required for drilling.
- Changes in strata are difficult to recognize between sample intervals.

- o Cross-contamination may occur due to the circulation of water between the casing and borehole wall.

- o Large quantities of water can be introduced into permeable formations.

- o Difficult to control release of drilling fluid at surface.

3.2-4.4 Problems and Possible Solutions

3.2-4.4.1 Lost Circulation

In highly permeable, unsaturated formations (e.g., sand and gravel deposits), fluid circulation may be lost into the formation during drilling because the rate of fluid loss through the bottom of the casing is greater than the pumping rate that can be maintain. As a result, the loss of the lubricating action of the water may destroy the shoe and cause the casing to "bind up." There are two options that can be used to overcome this problem:

(a) Increase the viscosity of the drilling fluid by the addition of additives as long as these additives will not influence the results of analytical testing of samples from the monitoring wells. Prior approval must be obtained from DEP before using any additives.

(b) Consider changing to another drilling method, such as cable tool. This may require a different drilling contractor.

3.2-4.4.2 Eroding a Large Hole

With this method it is possible to erode a large hole in the borehole wall, especially if an obstruction is encountered. A minimum amount of water should be used during drilling to help control this problem.

3.2-5 SOLID-STEM AUGER

3.2-5.1 General Considerations

Solid-stem auger drilling utilizes spiral, solid-center auger flights. The augers are screwed into the soil by a combination of downward pressure and rotating action. This method is not recommended for environmental studies. It is not recommended by DEP for determining soil characteristics or monitoring well installations unless the soil has been characterized previously by another drilling and sampling technique.

There is no provision for obtaining soil samples unless the auger is removed from the borehole. If soil sampling with a split-spoon is attempted, there is always the potential for caving of the borehole when the augers are removed, which would influence the quality of the sample recovered. Auger cuttings that come to the surface can be examined and a general stratigraphy described. Soil samples taken from the flights may misrepresent the actual formation material at the bottom depth of the augers.

The solid-stem auger method is more commonly used for probing to refusal or bedrock. See Figure 3.2-5 for an illustration of an auger drilling setup using a solid-stem auger.

Although the information obtained from solid-stem auger borings is limited, this method can be useful as a reconnaissance technique and for drilling pilot holes in fill and debris. Solid-stem augers should only be used under special conditions when it has been determined that plugging of the borehole will not be required. As with hollow-stem augers, the rigs are quite mobile and can access almost any site. Because no samples are collected, drilling is quite rapid and setups are minimal. The diameter of the drilled hole ranges from 4 to 20 inches.

3.2-5.2 Drilling Methodology

3.2-5.2.1 Drilling Operation

The lead auger is placed on the drill head, and the boring is advanced by a combination of rotation and downward pressure. Once the bottom of the auger reaches the desired depth, an additional auger may be added. If pins or bolts are used to attach the augers to each other, these should be secure before drilling continues.

Drilling can proceed quite rapidly with the addition of more augers. Drilling should continue until the boring has reached the desired depth or until refusal. Refusal means that the auger encounters substantial resistance and penetration is slowed or stopped. This may be caused by a boulder or by the auger encountering the bedrock surface. The distinction between the top of bedrock and a boulder is extremely difficult to determine. Bedrock can only be verified by rock coring methods.

3.2-5.2.2 Removal and Inspection of Cuttings

As drilling proceeds, the cuttings will travel up the outside of the augers to the ground surface. General soil characteristics can be described by examining the cuttings, although no information on soil structure can be obtained with this method. Generally, the best way to obtain a sample for inspection is to place a shovel at the top of hole and to collect a sample of the cuttings.

3.2-5.3 Advantages and Disadvantages

3.2-5.3.1 Advantages

- Especially suitable for cohesive, moderately dense soils which will remain open, uncased.
- Quick method for probing with generalized stratigraphic description possible.
- Rigs are able to access most terrains.

3.2-5.3.2 Disadvantages.

- Not generally suitable for monitoring well installation and for determining soil conditions.
- If the subsurface materials are contaminated, this method can result in cross-contamination, potentially affecting future subsurface investigations.
- Soil cuttings return is poor to non-existent below the water table.
- Refusal data is not always reliable for determining the top of bedrock, particularly in glacial till.
- Not suitable for sampling soft, unstable soils which will not remain open, if uncased.

3.2-6 HOLLOW-STEM AUGER

3.2-6.1 General Considerations

This method is suitable for unconsolidated deposits that do not have large cobbles or boulders. Hollow-stem augers are continuous augers equipped with a hollow core that serves as casing. Representative soil samples may be obtained by passing a sampling tool through the bottom of the lead hollow-stem auger. Monitoring wells can also be installed through the center of the augers. Figures 3.2-6 and 3.2-7 are examples of typical hollow-stem auger equipment.

Commonly, the inside diameter of the hollow-stem is 4 to 6 inches, and the augers produce a borehole 8 to 12 inches in diameter. Auger rigs are skid-, truck-, or track-mounted, giving them excellent mobility. This drilling method is relatively fast, depending on soil sampling requirements.

Hollow-stem auger methods have significant limitations in investigations in contaminated areas due to the potential for cross-contamination in the borehole. Contaminated cuttings moving up an auger flight may contaminate overlying clean zones. In other cases, contaminated auger flights penetrating to greater depths may carry contamination down with them.

Additionally, the rotating action of the augers causes a smearing in fine-grained soils. This smearing may significantly reduce the permeability in the vicinity of the borehole, resulting in erroneous estimates of in-situ permeability from field tests. Furthermore, this smearing may effectively seal off a zone opposite the proposed screened interval of a monitoring well, and well development may not be adequate to overcome this effect.

3.2-6.2 Drilling Methodology

3.2-6.2.1 Drilling Operation

The lead auger should be attached to the drill head. In order to assist in cutting the borehole, auger teeth (i.e., sharp, protruding, carbide-capped metal tabs) are located at the tip of the lead auger. This auger is drilled or "screwed" into the ground by a combination of rotation and downward pressure. If obstructions are encountered, the auger may "walk," causing the borehole to become crooked or deflected from vertical. If this occurs at a shallow depth, it is advisable to move the boring location slightly and start the hole again.

During advancement, a removable center plug (pilot bit) or split-spoon sampler is attached to the drill rods and placed in the bottom of the lead auger to prevent soil materials from entering the hollow stem. When a required depth is reached, the center plug can be removed and representative samples obtained by passing a sampling tool through the hollow stem of the auger and out the bottom.

Once the augers have reached the desired depth and a sample has been collected, drilling can continue. The center plug is replaced in the bottom of the lead auger and an additional auger flight is attached. If the augers are attached to each other with bolts or pins, it is important that they be secured before drilling proceeds. Failure to do this can result in detachment of the augers below the ground surface.

3.2-6.2.2 Removal and Inspection of Cuttings

During drilling, the cuttings from the borehole are carried upward to the ground surface along the outside of the augers on the screw-shaped auger flights. These cuttings are usually shoveled to the side, where they can be inspected. In some cases, stratigraphic changes can be observed due to significant changes in the cuttings or the drilling action of the auger. In some soil conditions, such as fine sands, once the augers are below the top of the saturated zone the cuttings may not travel to the surface along the outside of the auger flights. When this happens, standard split-spoon samples may be the only way to collect and determine the soil characteristics.

Once the auger flight has reached the required depth, soil samples can be collected. A sampling tool can then be lowered down through the hollow center of the auger and a sample can be obtained.

Recently, a new method of obtaining soil samples with hollow stem augers has been developed which uses an inner tube sampler. This sampler consists of an inner split-barrel tube, typically 4-inches in diameter, that is placed inside the lead auger. As the borehole is advanced, the soil material enters the tube for the length of the drilling interval, similar to the way rock core enters a core barrel. Once the interval is completed the augers are detached from the drive head and the tube is removed with the drill rods. The split-barrel tube is removed and opened in a manner similar to a split-spoon. This sampling method allows rapid, continuous sampling in hollow-stem auger holes and is best suited for fine-grained soils such as silts and clays.

3.2-6.3 Advantages and Disadvantages

3.2-6.3.1 Advantages

- Water is usually not required.
- Fast drilling technique in soft and fine-grained soils.
- Quick set-ups possible.
- Can install well casing inside hollow-stem auger.
- Representative samples can be obtained.

3.2-6.3.2 Disadvantages

- Difficult to use in very dense or boulder-rich soils.
- Monitoring well installation quality may vary from good to poor due to small diameter opening in the augers, a disturbed interface with formation soils, and the fact that the augers are generally rotated out of the hole.
- Can be difficult to obtain samples of silts and sands beneath the water table as "quick" (i.e., running sand) conditions may be present.
- Frictional resistance from fine sand or nested boulders may tend to lock the augers in the ground.
- Due to the constant rotation of the augers, smearing of fine-grained soil material may occur on the sidewalls of the borehole.
- Potential for cross-contamination within the borehole at contaminated sites.
- Good seals around the top of the sand packs may be difficult to achieve due to the large annular space and the presence of a zone of disturbed soil materials in the annular space, once the augers are removed.

3.2-6.4 Problems and Possible Solutions

3.2-6.4.1 Sand or Silt Flowing Up Inside the Auger; "Running Sands"

When drilling below the water table, sands may run up into the center of the augers when the center plug is removed. An unbalanced hydrostatic head is created if water is not added to the augers during the advancement of the borehole. Unbalanced heads can also occur during the sampling as discussed in the subsection on the drive and wash method (see Section 3.2-3.4.2). These problems may be overcome by removing all downhole tools (including the center plug) very slowly or by introducing water into the auger or both simultaneously.

3.2-6.4.2 Health and Safety Problems

Health and safety problems generally involve the increased volume of potentially contaminated soils produced by this method. When required, special drill-through containers can be used to catch and hold the auger cuttings to minimize potential spread of hazardous materials and contact with workers.

3.2-7 MUD ROTARY

3.2-7.1 General Considerations

Mud rotary drilling methods should not be employed for environmental investigations at either state or privately funded sites except with the specific, prior approval of DEP. The use of mud rotary techniques should be fully documented by the driller and described by the consultant in his report. Although mud rotary is a popular exploration drilling method, it has limited application in hydrogeologic investigations since use of drilling mud results in many problems from a hydrogeologic and chemical standpoint. For example, drilling mud may significantly lower the permeability in the adjacent formation. Also, mud residues are difficult to remove with standard well development techniques. Because of the potential for cross-contamination in the borehole, recirculation of the drilling mud is a concern where contaminated zones are encountered. Also, mud residues may alter the groundwater chemistry by binding metals, adsorbing organics, altering the pH, or changing COD conditions.

In mud rotary drilling a bit, usually a tricone, is placed on the bottom of the drill stem, and the rotating action of the bit crushes and grinds the subsurface materials into small pieces. Simultaneously, drilling fluid (usually a bentonite drilling mud) is pumped down through the center of the drill pipe and circulates up the borehole, carrying the cuttings up and out of the hole. The "dirty" drilling mud is directed to a mud pit or baffled tank where the cuttings are allowed to settle. Once the drilling mud is relatively clean, it is recirculated down the borehole. Efficient mud rotary operation requires an experienced driller who is familiar with the proper drilling and mud mixing techniques for various geologic conditions. Figures 3.2-8 through 3.2-10 illustrate typical set-ups for mud rotary drilling and equipment.

In mud rotary drilling, the drilling fluid stabilizes the borehole sidewalls, cools the bit, and brings the cuttings up out of the borehole. One significant advantage of mud rotary over many other drilling techniques is that in most applications, casing is not required to stabilize the borehole sidewalls, resulting in much faster drilling. The hydrostatic pressure of the column of drilling fluid in the borehole prevents caving of the sidewalls. As drilling proceeds, a film of clay particles builds up on the borehole walls to form a filter cake lining the sidewalls. This "clay casing" prevents erosion of the walls by the circulating drilling fluid and reduces or prevents fluid loss into the formation.

Mud rotary holes vary from 3- to 28-inches in diameter, with 6- to 8-inch holes being the most common. Mud rotary methods can be used to drill to depths of 500 feet and greater.

3.2-7.2 Drilling Methodology

3.2-7.2.1 Drilling Operation

Mud rotary drilling requires a substantial setup and a fairly large working area. Prior to drilling, adequate water and mud (usually bentonite) should be prepared in advance so that the drilling process need not be interrupted. The water should be clean, as the quality of the mud can be seriously affected by contaminants or water with a high mineral content. Prior to drilling, a quantity of drilling mud is mixed either in mud pits, tubs, or tanks. The viscosity and quantity of the mud will be dependent on the anticipated geologic conditions and the depth and diameter of the borehole.
Typically, mud rotary borings are advanced in intervals equal to the length of a drill rod. As the boring is advanced by a combination of rotation and downward pressure, additional mud may be mixed and added due to the increased volume of the hole and losses due to infiltration in very coarse material. If the formation conditions change, the mix may have to be modified.

It is important that a drill collar (sometimes referred to as a stabilizer), a larger diameter, heavier length of drill pipe, be placed on the drill stem immediately above the bit. The drill collar helps to maintain a straight hole during drilling.

If the boring is penetrating very soft or caving formations, a surface casing may be set to keep the borehole walls from collapsing. The surface casing usually has a discharge pipe connected to the top to direct the drilling mud into the settling tank.

3.2-7.2.2 Removal and Inspection of Cuttings

Generally, mud rotary samples consist only of samples of the cuttings that come up out of the borehole. A strainer can be used to collect the cuttings and, after rinsing them with clear water, they can be described. Mud rotary methods can be modified to obtain representative geologic samples, such as split-spoon samples, although this slows down the drilling progress significantly.

3.2-7.3 Advantages and Disadvantages

3.2-7.3.1 Advantages

- Rapid drilling method in most geologic conditions.

- Generally no casing is required during drilling.

- Can drill deep borings, 500 ft. or greater, under most conditions.

3.2-7.3.2 Disadvantages

- Drilling mud may adversely affect water-quality, permeability, and well development parameters. During drilling, mud may mask geologic details and water-bearing zones.

- Cross-contamination potential is high.

- Cold weather drilling is difficult due to mud mixing requirements.

3.2-7.4 Problems and Possible Solutions

3.2-7.4.1 Lost Circulation

Lost circulation occurs in porous, granular, or jointed formations when the drilling fluid cannot be maintained in the hole. Lost circulation can lead to caving of the borehole and loss of the drilling tools. Three methods are used to remedy lost circulation problems:

- Increase the viscosity of the drilling fluid.

- Case off the permeable zone.

- Add wash circulation material (i.e., mica flakes, peanut hulls) to increase viscosity of the drilling fluid; this method is only appropriate for explorations when contamination is not present or anticipated.

Once a lost circulation problem occurs, efforts should be taken immediately to avoid losing excessive amounts of drilling fluid into the formation.

3.2-7.4.2 Crooked Holes

A straight hole is essential for drilling, particularly for deep borings. Crooked holes are most likely to occur in hard formations, especially those with large boulders, dipping structures, or numerous fractures. Proper selection of bits and stabilizers will help to avoid the development of crooked holes. Generally, the best method to straighten a crooked hole is to ream or enlarge the hole size. If this does not work effectively, it may be best to abandon the hole and start a new one.

A crooked hole may be difficult to detect. One indication of a crooked hole is excessive wear on the drill string. The wear occurs where the hole orientation is deflected and results in abrasion of the drill stem.

3.2-7.4.3 Stuck Bits and Rods

In any rotary method, drill rods and bits will occasionally become "grouted" in the hole due to the settlement of cuttings around the bit. Shaking the rods and circulating drilling fluid may help to loosen the drill stem. If excessive amounts of sand remain in suspension in the drilling fluid, it may be necessary to send the fluid through a de-sander prior to recirculation down the drill hole. The de-sander uses centrifugal motion to separate the sand from the fluid, reducing the amount of suspended sand.

3.2-8 AIR ROTARY/AIR HAMMER

3.2-8.1 Drilling Methodology

The procedure is similar to mud rotary, except that air rather than mud is used as a drilling fluid to cool the bit and bring the cuttings out of the hole. A guide for the use of bit types with air drilling systems is presented in Table 3.2-7. The primary reason for using air hammer or rotary techniques is that it is a cost-effective method to rapidly advance a deep hole in dense, unconsolidated and consolidated material for monitoring well installation.

3.2-8.1.1 Drilling Operation

A large compressor on the drill rig provides air for the drilling operation. Occasionally, a small amount of water is added to the air system to reduce the air-borne dust and to cool the bit. Similar to mud rotary, a rotating tricone at the bottom of drill stem chips and cuts the formation. At the same time, air is forced down the inside of the drill stem to blow the cuttings up and out of the hole.

Air rotary rigs are generally used in dense, unconsolidated and hard rock formations. This drilling method is unsuitable for loose, unconsolidated formations because the installation of casing is required. Often, air rotary rigs are equipped with both fluid- and air-based equipment, allowing the overburden to be drilled with fluid rotary techniques, casing to be installed, and bedrock to be drilled using air techniques. Figures 3.2-11 and 3.2-12 depict the equipment and typical set-up for air rotary drilling.

Air hammer or "down-the-hole hammer" drilling methods use a pneumatic hammer to break up the rock into fine particles. Air is used to remove the cuttings from the borehole and from the cutting surface on the rock. Air hammer holes are typically 6- to 9-inches in diameter, although holes as large as 18 inches have been drilled successfully. Air hammer techniques are used in hard, consolidated formations, such as the bedrock typical of New England, where other drilling methods are slow or unsuitable.

3.2-8.1.2 Removal and Inspection of Cuttings

Sample collection is limited to obtaining a portion of the borehole cuttings. Generally, the cuttings are quite fine-grained and provide only extremely limited information on the rock characteristics.

3.2-8.2 Advantages and Disadvantages

3.2-8.2.1 Advantages

- Drilling is very rapid compared to other drilling techniques, especially for very hard rock formations.
- Drilling can be done year round.
- Little or no water is necessary to complete boring.

3.2-8.2.2 Disadvantages

- Rigs are generally quite large and cannot access wet or sloping sites without the construction of a road.
- Undisturbed or representative samples are not practical.
- Not generally suitable for drilling in loose, unconsolidated deposits; casing must be used in soft or caving formations; only suitable for dense, unconsolidated or consolidated formations.

- Cross-contamination can occur in the borehole due to circulation up and down an open, uncased hole; therefore, may be unsuitable for use at contaminated sites.

- Minimum borehole diameter is six inches.

- Difficult to identify potentiometric surface.

- At a contaminated site, air emissions may be a significant health and safety concern.

- Potential for contamination from compressor oil.

3.2-8.3 Problems and Possible Solutions

3.2-8.3.1 Contaminated Air Injected Into Boring

Air rotary rigs use lubricants and oils in the compressor. Filters should be used to minimize contamination from oils and lubricants. Filters will remove particulate and droplets of oil but not 100 percent of hydrocarbon vapors. It should be noted that the quality of the ambient air may be impacted from drill rig exhaust; this cannot be avoided. If the hydrogeologic objective(s) include a contamination assessment, care must be taken to ensure that an effective filter is used and that the air injected into the hole is uncontaminated.

3.2-8.3.2 Air Emission Hazards

The air-borne emissions resulting from air drilling methods may be difficult to control during drilling. If hazardous contaminants are encountered in the borehole, they may be blown to the surface with the cuttings, posing a potential hazard to the drill crew and inspector. Air drilling methods are generally unsuitable for highly contaminated, subsurface conditions due to the potential for personal exposure and cross-contamination.

3.2-9 ODEX SYSTEM

3.2-9.1 General Considerations

The ODEX drilling method has been adapted from an air percussion drilling method used in the construction industry to install earth anchors and tie-backs. The standard percussion drilling equipment has been modified to allow for the installation of a heavy-duty temporary casing. The ODEX method is capable of drilling 3- to 6-inch diameter holes in unconsolidated materials and bedrock. Conventional sampling is possible with a slight modification of the drilling method. Figures 3.2-13 and 3.2-14 are schematics of the drilling equipment used in the ODEX system.

The ODEX method is suitable for unconsolidated materials, or down-hole hammer drilling in bedrock, although conventional rock coring can be accomplished through the use of temporary casing. The ODEX drilling system is suitable for most soil conditions, although the bit has a tendency to plug in cohesive, granular soils with fines.

3.2-9.2 Drilling Methodology

The boring is advanced to the required depth by a combination of pilot and reamer bits. This drilling method incorporates simultaneous advancement of the boring with the pilot bit and enlargement with the eccentric reamer bit to the desired depth. When the drilling is completed, the pilot bit is rotated in the opposite direction, aligning the bit with the eccentric reamer. Once they are re-aligned, the drill tools can be withdrawn from the borehole (Figure 3.2-13) and a sampling device can be used to collect a representative sample.

During the advancement of the boring, temporary steel casing is installed directly behind the reamer bits. The casing is driven into place by a percussion motion without rotation (Figure 3.2-14). Following completion of the boring, the casing can be removed. If a permanent casing is desired, the steel casing can be replaced with a less expensive, smaller-diameter casing. The permanent casing is installed inside the temporary steel casing, and the steel casing is withdrawn.

3.2-9.3 Advantages and Disadvantages

3.2-9.3.1 Advantages.

- Drilling method is extremely fast and cost-effective.
- Provides for the installation of temporary and/or permanent casing.
- Limited use of water to cool the cutting bit is necessary in the drilling method.
- Small rigs can be used on most terrains and under most weather conditions.
- Borings can be used to install monitoring wells or instrumentation.
- Standard soil samples can be obtained.

3.2-9.3.2 Disadvantages

- o Soil sampling may result in a significant reduction in drilling rate.
- o Requires an air compressor; air must be filtered to minimize volatile contamination.
- o Specialized equipment not readily available in all parts of Massachusetts; requires experienced operator.
- o Not suitable for fine-grained soils due to problems with the bit plugging.
- o Air emissions may be a problem at contaminated sites due to volatile and aerosol material discharged to the work environment.

3.2-10 DRILLING FLUIDS

Several types of drilling fluids, including water, air, mud, polymers, and surfactants, are used in the completion of borings. In environmental investigations, clean water is the most commonly used fluid. Mud is used occasionally. Surfactants and polymers are rarely used in environmental investigations and, consequently, will not be discussed here. The use of any drilling fluid, other than air and potable water, requires prior approval by DEP. At other sites the use of drilling fluids other than air or potable water should be fully documented by the driller and described in the consultant's report.

3.2-10.1 Functions of Drilling Fluids

The selection of a specific drilling fluid will depend on the drilling equipment to be used, the nature of the soil and rock materials, and the constraints of the investigation. The primary functions of drilling fluids are, as follows:

- o To remove cuttings from the borehole.
- o To stabilize the borehole.
- o To cool and lubricate the drill bit.
- o To control fluid loss in highly permeable formations.

In addition, drilling fluids provide information, in the form of cuttings, about the generalized borehole stratigraphy.

3.2-10.2 Factors Affecting Performance

The ability of a drilling fluid to perform these functions is related to the following factors:

- o Viscosity - The resistance of liquids, semi-solids, and gases to movement or flow; a liquid having a high viscosity rating will resist flow more than a liquid having a low viscosity.

- o Density - The mass of a substance per unit volume; the ratio of the mass of any volume of a substance to the mass of an equal volume of a standard substance. For example, water is used as the standard substance to which the ratio of a quantity of a drill mud is compared. Density is expressed in units of pounds per gallon, pounds per cubic ft, and kilograms per cubic meter.

- o Discharge - Outflow from a pump, drill hole, piping system, or other mechanism.

- o Drill Fluid - Usually water or mud-laden water (sometimes applied to compressed air, natural gas, or oil) circulated through a drill string to keep the bit cool and to wash produced cuttings away from the bit face; also called circulation fluid.

- o Gel - A form of matter in a colloidal state that does not dissolve but remains suspended in a solvent from which it fails to precipitate without the intervention of heat or an electrolyte. A colloidal suspension exists in such a state that shearing stresses below a certain finite value fails to produce permanent deformation. The minimum shearing stress which will produce permanent deformation is known as the shear or gel strength of the gel. Gels commonly occur with bentonite in water.

- o Yield Point (yield value) - Stress needed to deform a plastic system sufficiently to initiate flow.

3.2-10.3 Types of Drilling Fluids

3.2-10.3.1 Water

In environmental investigations, water is the most commonly used and preferred drilling fluid. In small-diameter borings, 4-inches or less, water is quite effective in removing soil and rock cuttings during drilling. In most cases the cuttings drop out of the water quite easily when discharged into a settling tank. In certain materials, especially clays and rock, the cuttings may remain in suspension for long periods of time and, when recirculated, result in clogging of the drill rods and drill stem. The easiest remedy is to replace the drilling water with fresh, clean water when it becomes too thick or dirty.

In both rotary and bedrock coring drilling methods, water is used to cool and lubricate the bit. Loss of circulation, due to blockage or formation conditions, can quickly destroy drilling tools. Water flow may be monitored by observing flow meters generally located on the rig and by monitoring the volume of wash water discharge. Even small quantities of water lost into the formation can be detected by a gradual lowering of the water level in the discharge tank.

Water is not capable of performing all the functions desired in a drilling fluid. Water does not have the proper viscosity and density to stabilize and support the wall in uncased borings. Water is lost into permeable formations. This may be undesirable due to the addition of non-representative fluids to the aquifer and due to the drilling difficulties encountered when circulation is lost. Except for very fine-grained materials, water is not capable of suspending cuttings in a borehole for extended periods of time. Because of this, boreholes should be thoroughly flushed if drilling is interrupted. Bits should be left a short distance off the bottom of the hole to avoid trapping the bit in the settled soil and rock cuttings.

Water has the significant advantage that, in small quantities, it will have a minimal impact on the existing aquifer chemistry. In all drilling applications, only clean, potable water should be used. In contamination investigations, the drilling water should be tested prior to and periodically during drilling to assure that it is of suitable quality. In contamination investigations, only clean water is an acceptable drilling fluid.

3.2-10.3.2 Drilling Mud

Drilling mud is a general term applied to several types of bentonite-based drilling fluids. As previously described, these fluids consist of a mixture of bentonite and water. Bentonite, a naturally occurring sodium montmorillonite clay, is added to water to increase its viscosity, density, gel strength, and lubrication capacity. The plate-shaped clay particles expand in water and remain in colloidal suspension. Properly mixed drilling fluid is capable of removing the cuttings, stabilizing the hole, and permitting the cuttings to settle out before recirculating. Drilling muds have been developed primarily for large-diameter rotary holes where the annular space and size of the suspended particles are too large for water to be an effective drilling fluid. A significant advantage of drilling mud is that it eliminates the need for the use of casing. The use of drilling mud substantially speeds up a drilling program but is not acceptable in most environmental investigations due to the effects of the mud on the borehole permeability and chemistry. Experience has shown that drilling muds are very difficult to remove even after vigorous well development and purging. Appropriate applications of bentonite-based drilling fluids in environmentally sensitive investigations might include:

- Drilling pilot holes through thick, unsaturated, coarse-grained deposits where other techniques are ineffective.

- Drilling fast reconnaissance borings as part of a preliminary investigation.

- Completing borings for specific geotechnical or geophysical assessments.

- Under some conditions the use of mud may minimize the potential for cross-contamination during drilling.

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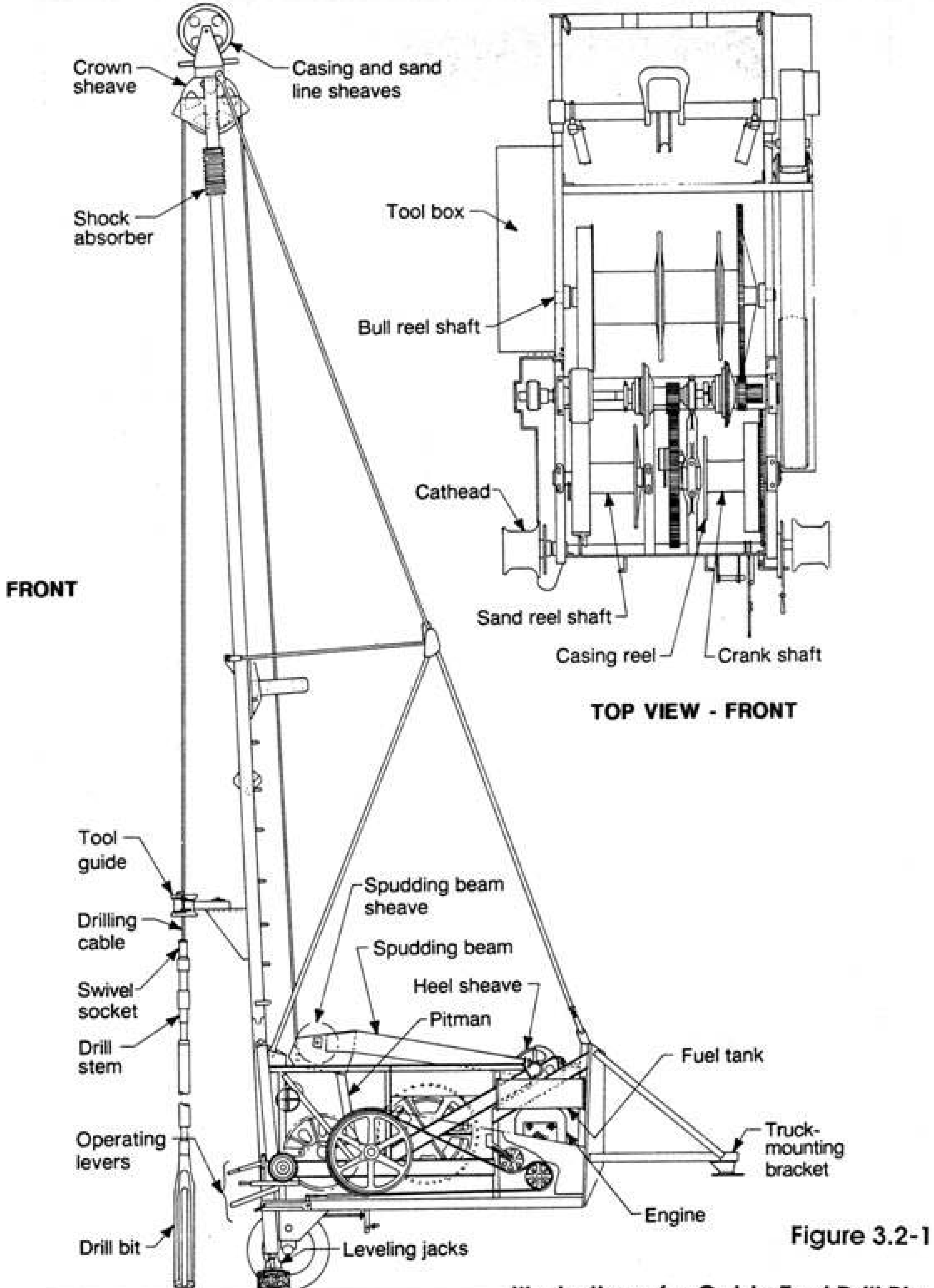


Figure 3.2-1

Illustration of a Cable Tool Drill Rig.

Source: Driscoll (1986)

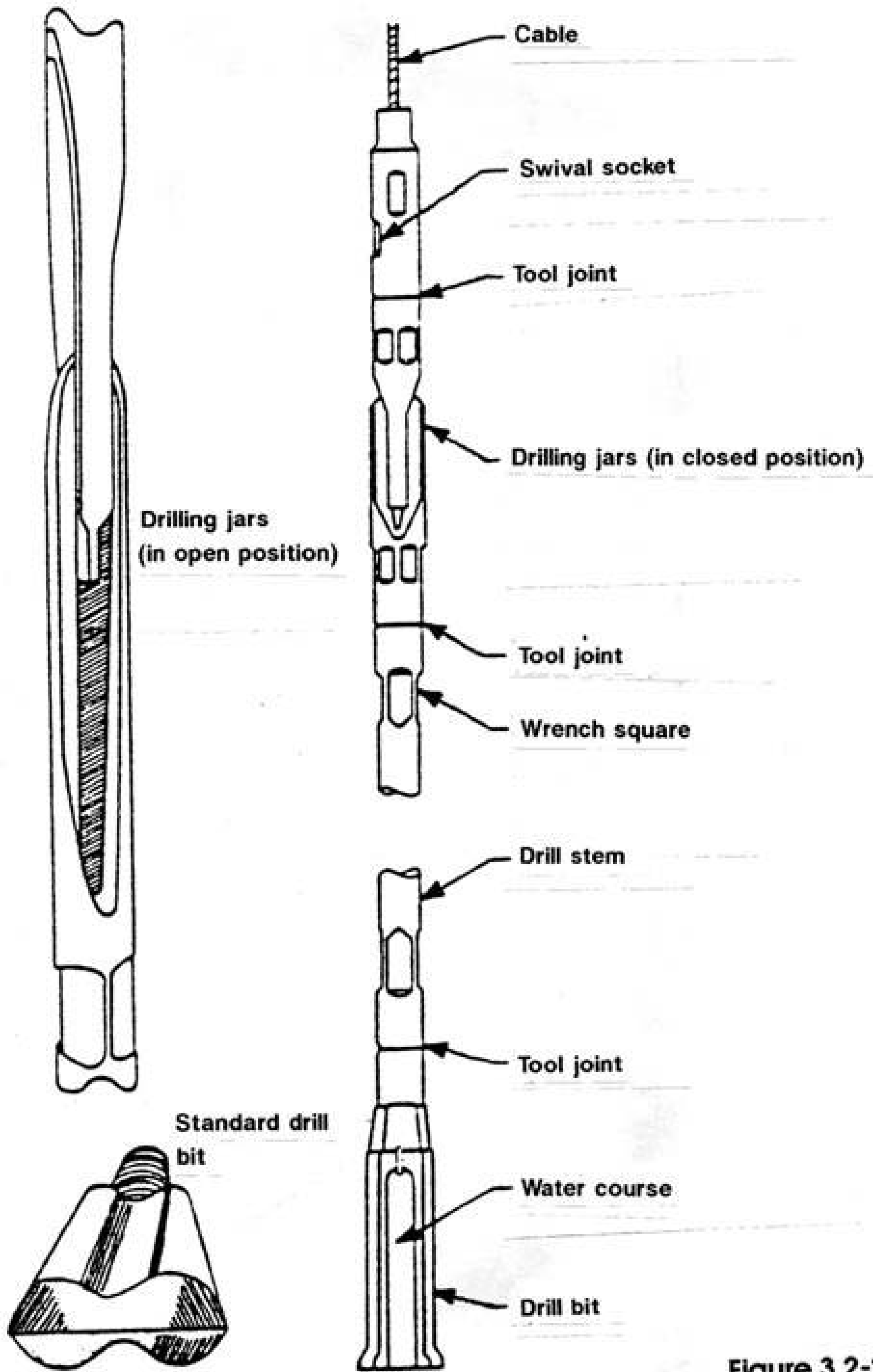
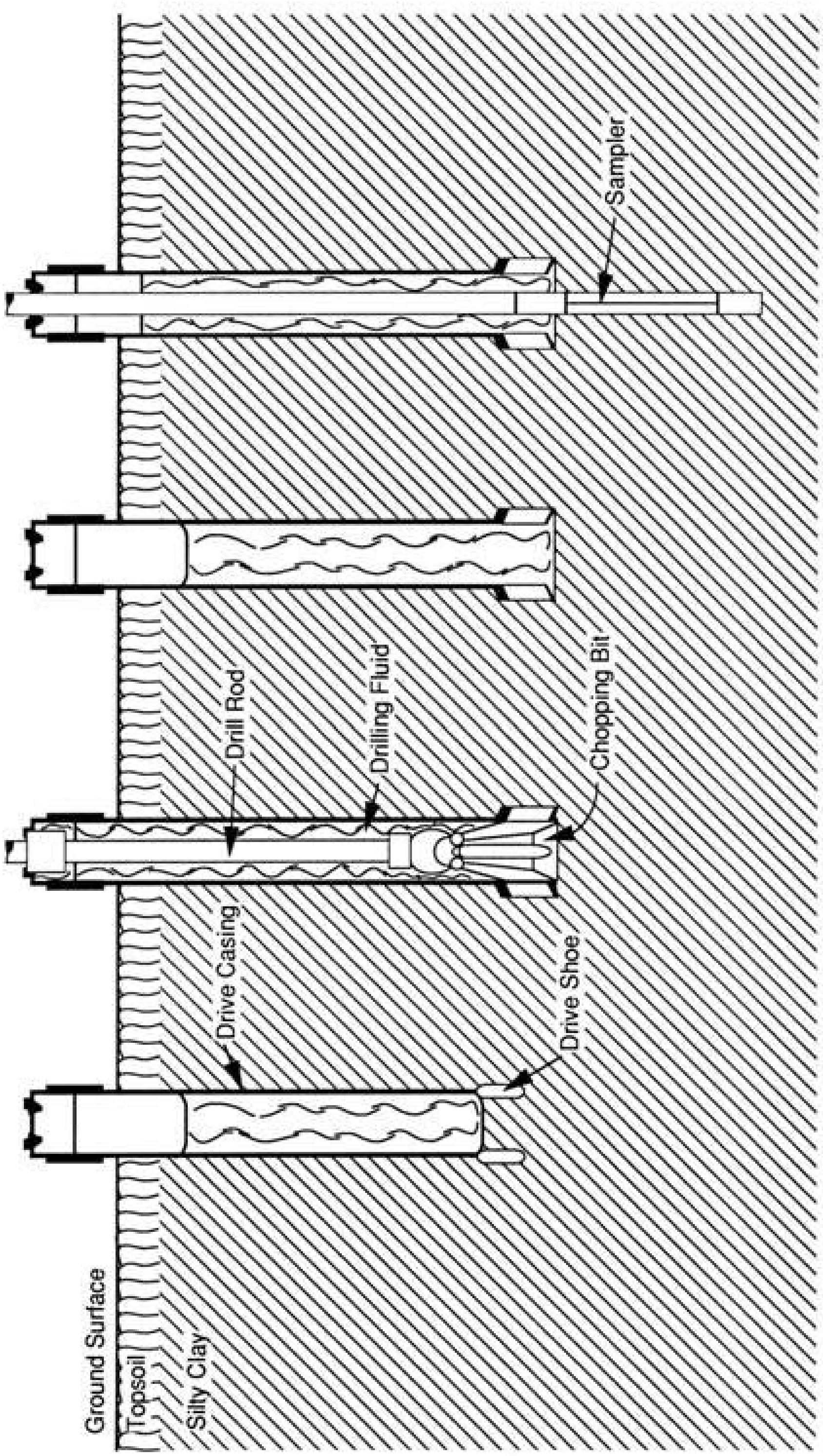


Figure 3.2-2

Cable Rig Drilling Tools.

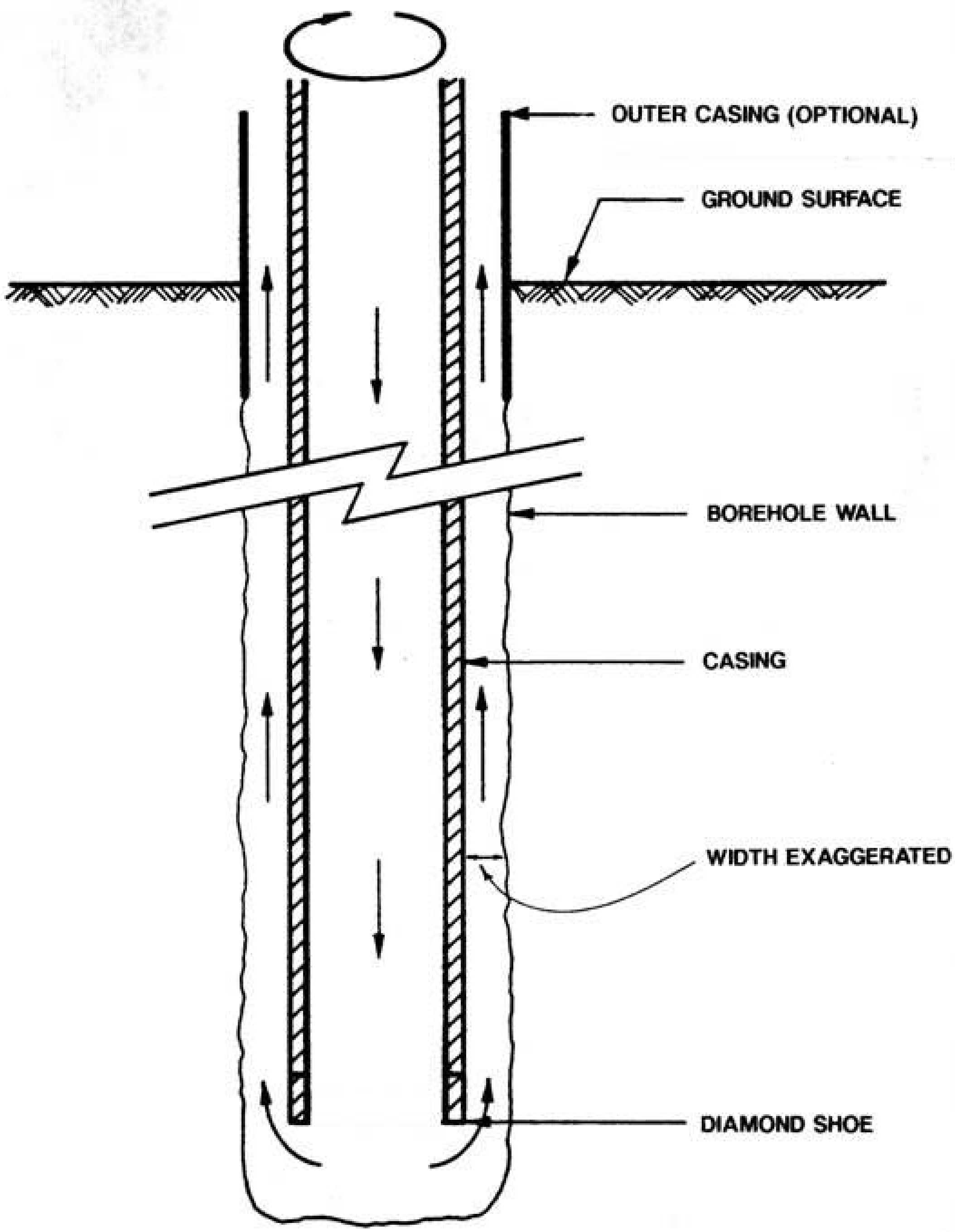
Source: Driscoll (1986)



Source: MADEP

Figure 3.2-3

Schematic of Drive and Wash Drilling Method.



NOT TO SCALE

Source: MADEP

Figure 3.2-4

Schematic of Spun Casing Drilling Method.

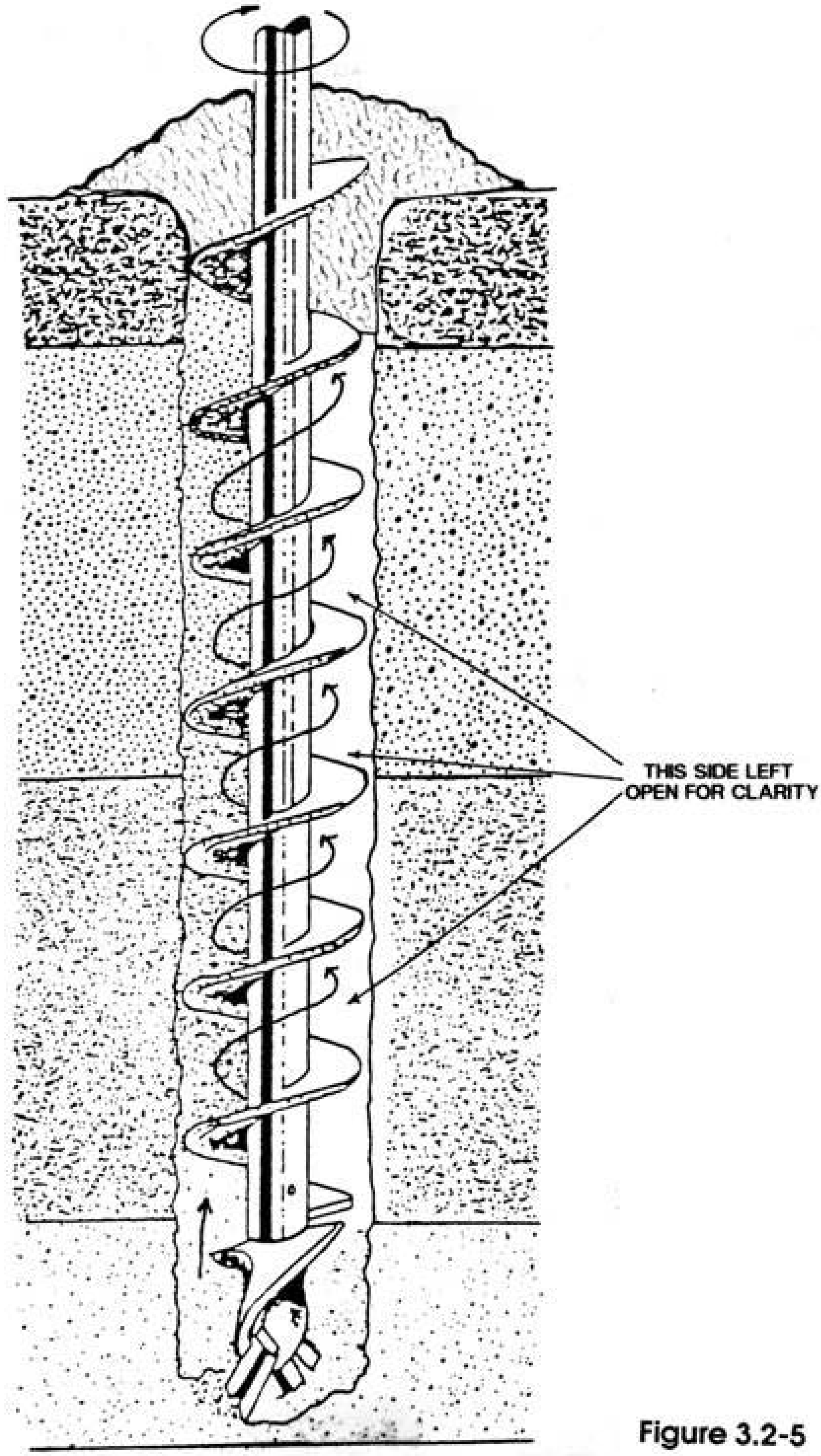


Figure 3.2-5

Source: After Scalf et al. (1981)

Schematic of Auger Drilling Method.

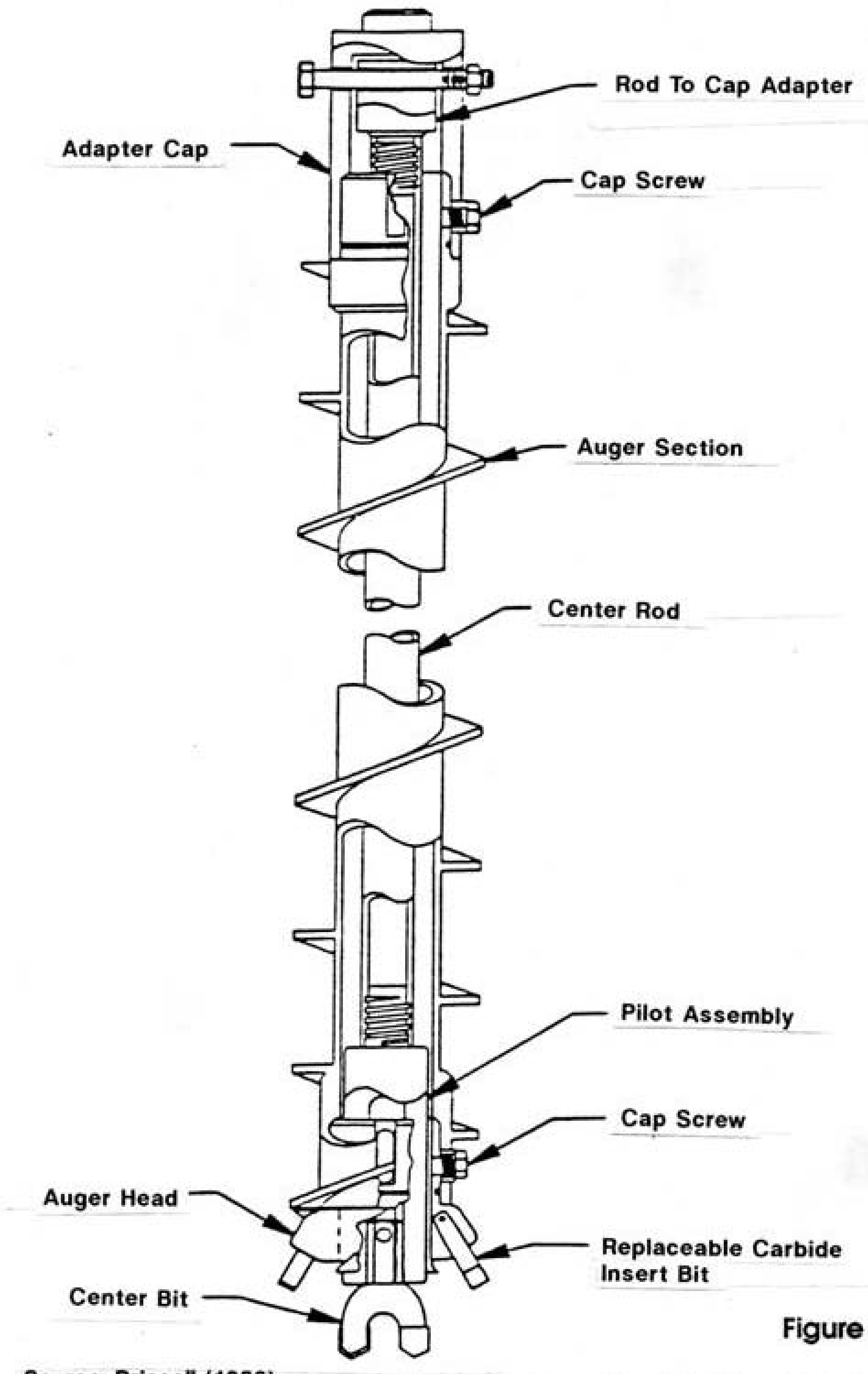
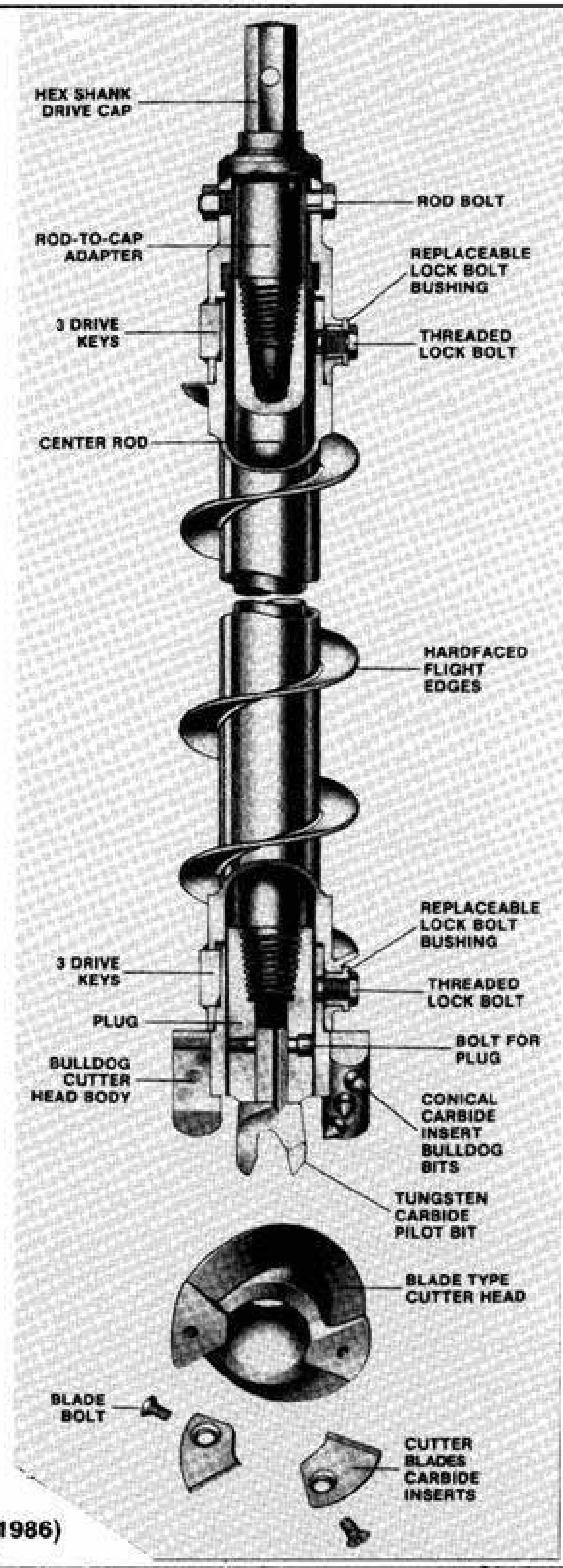


Figure 3.2-6

Source: Driscoll (1986)

Components of Hollow-stem Auger.



Source: Driscoll (1986)

Figure 3.2-7

Detail of Lead Hollow-stem Auger.

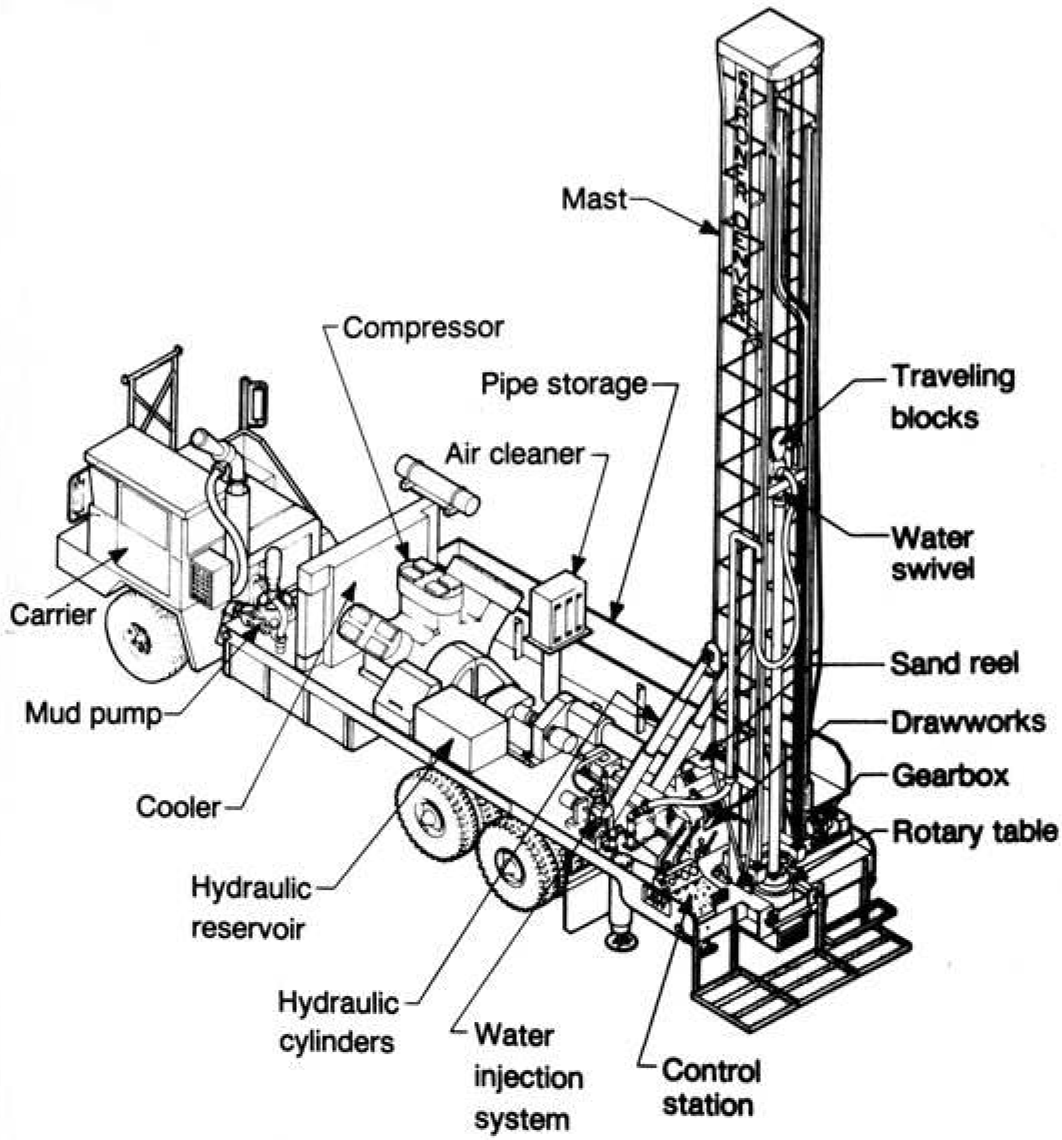
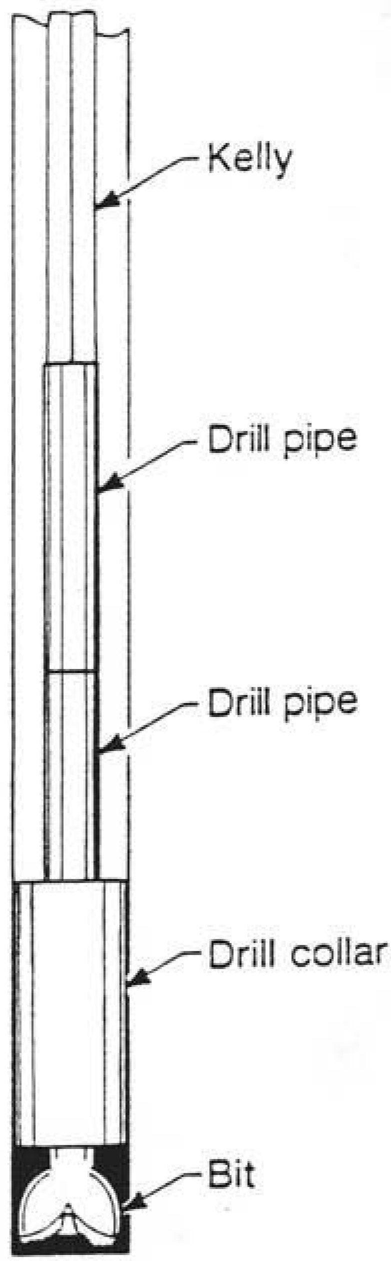


Figure 3.2-8

Source: Driscoll (1986)

Schematic of Rotary Drill Rig.

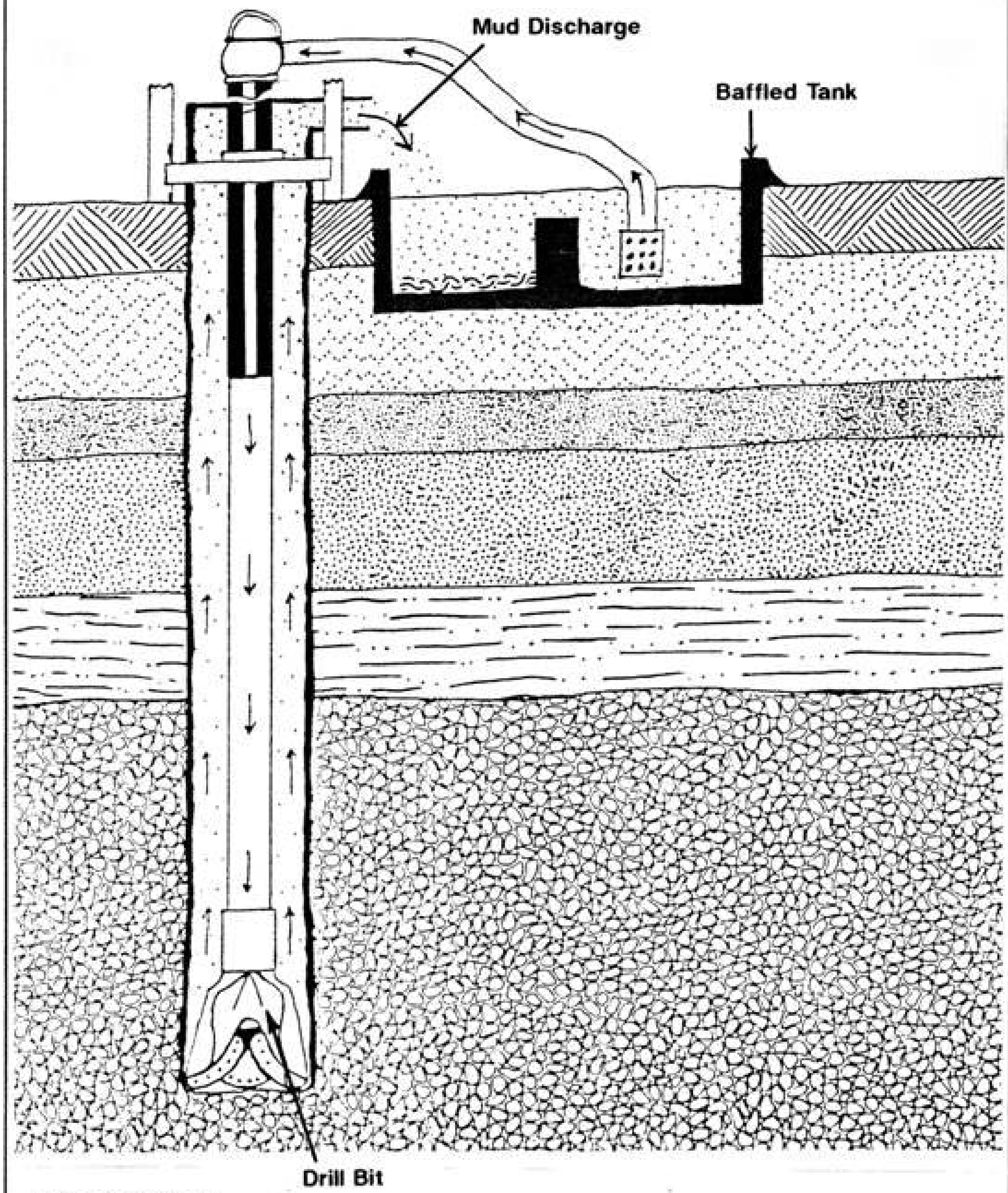


NOT TO SCALE

Source: Driscoll (1986)

Figure 3.2-9

Drill String for Mud Rotary Drilling Method.



Source: After Scalf et al. (1981)

Figure 3.2-10

Schematic of Mud Rotary Drilling Method.

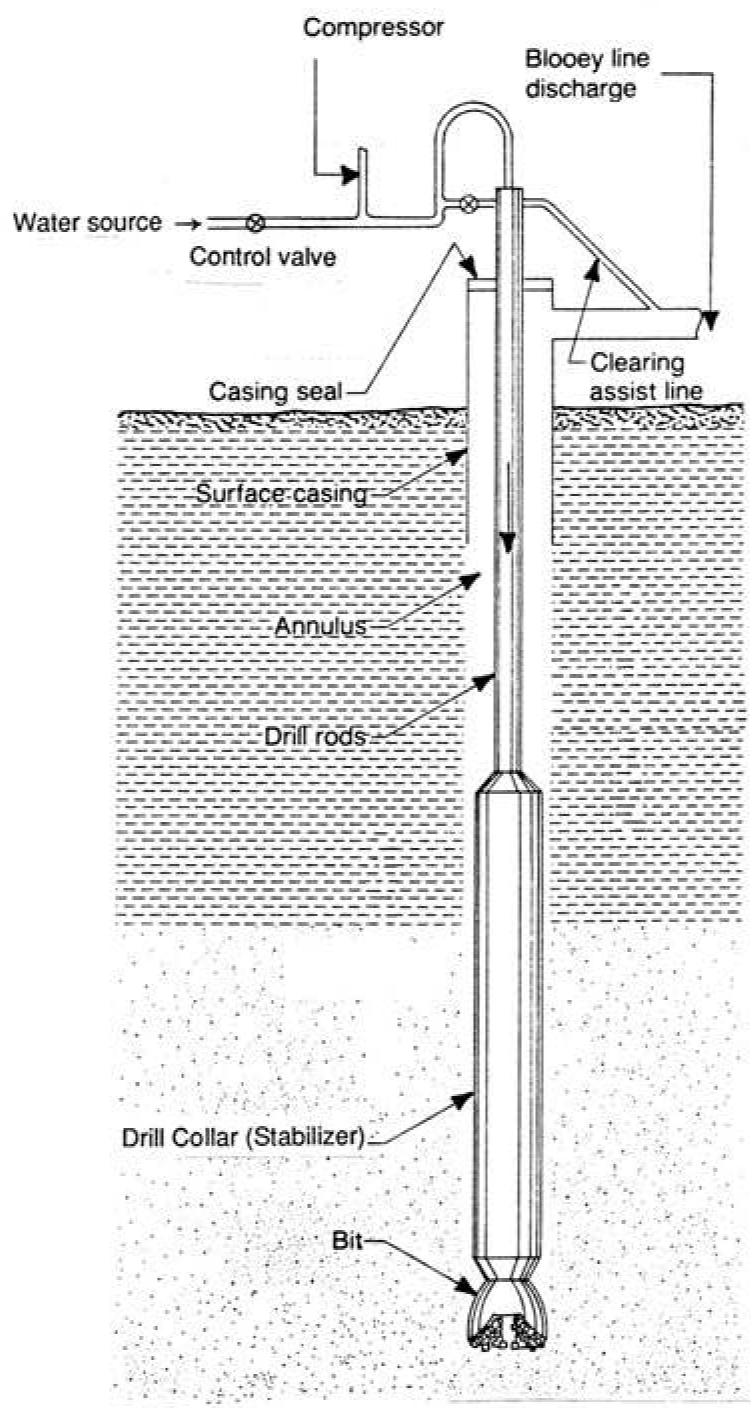


Figure 3.2-11

Source: Driscoll (1986)

Schematic of Air Rotary Drilling Method.

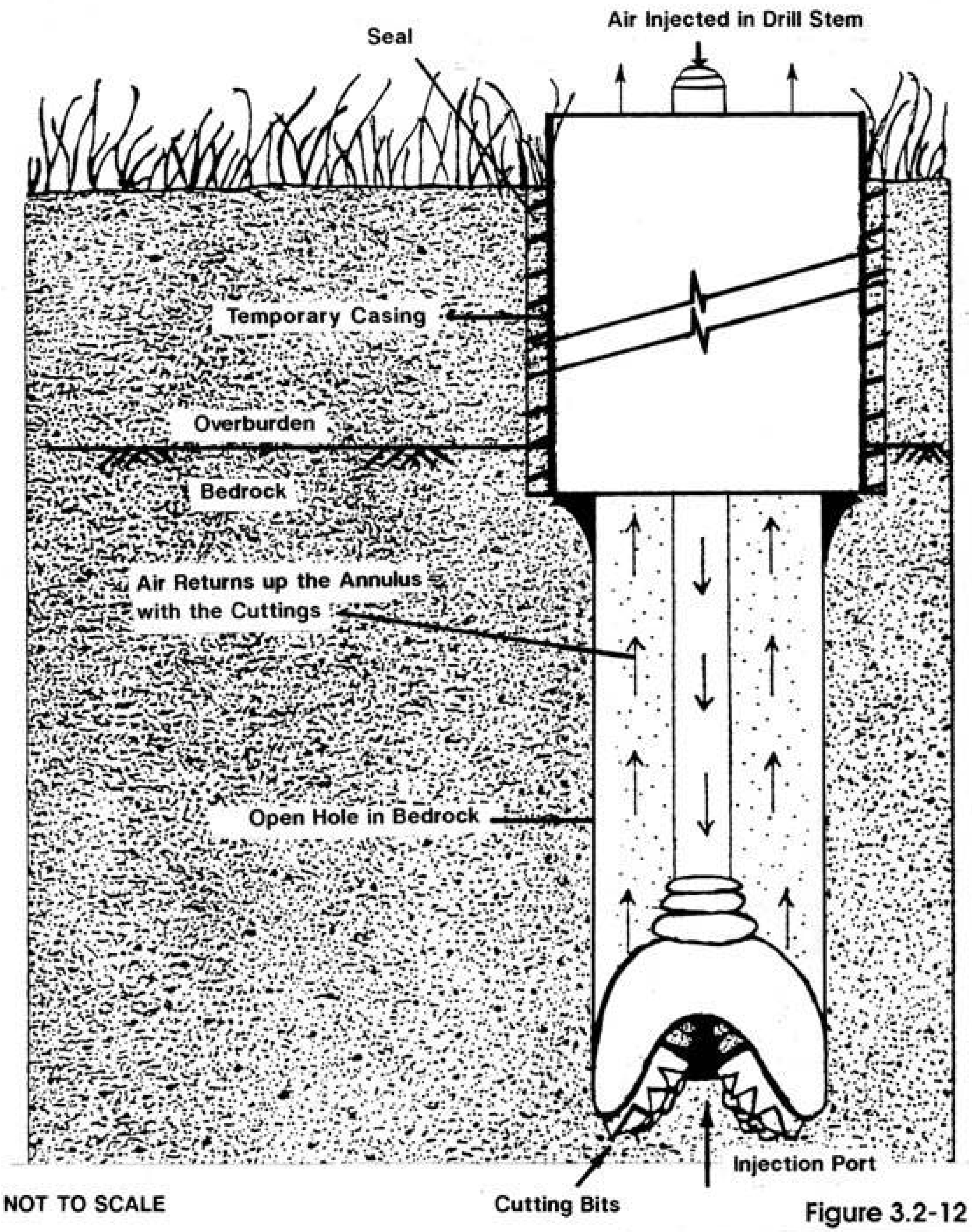
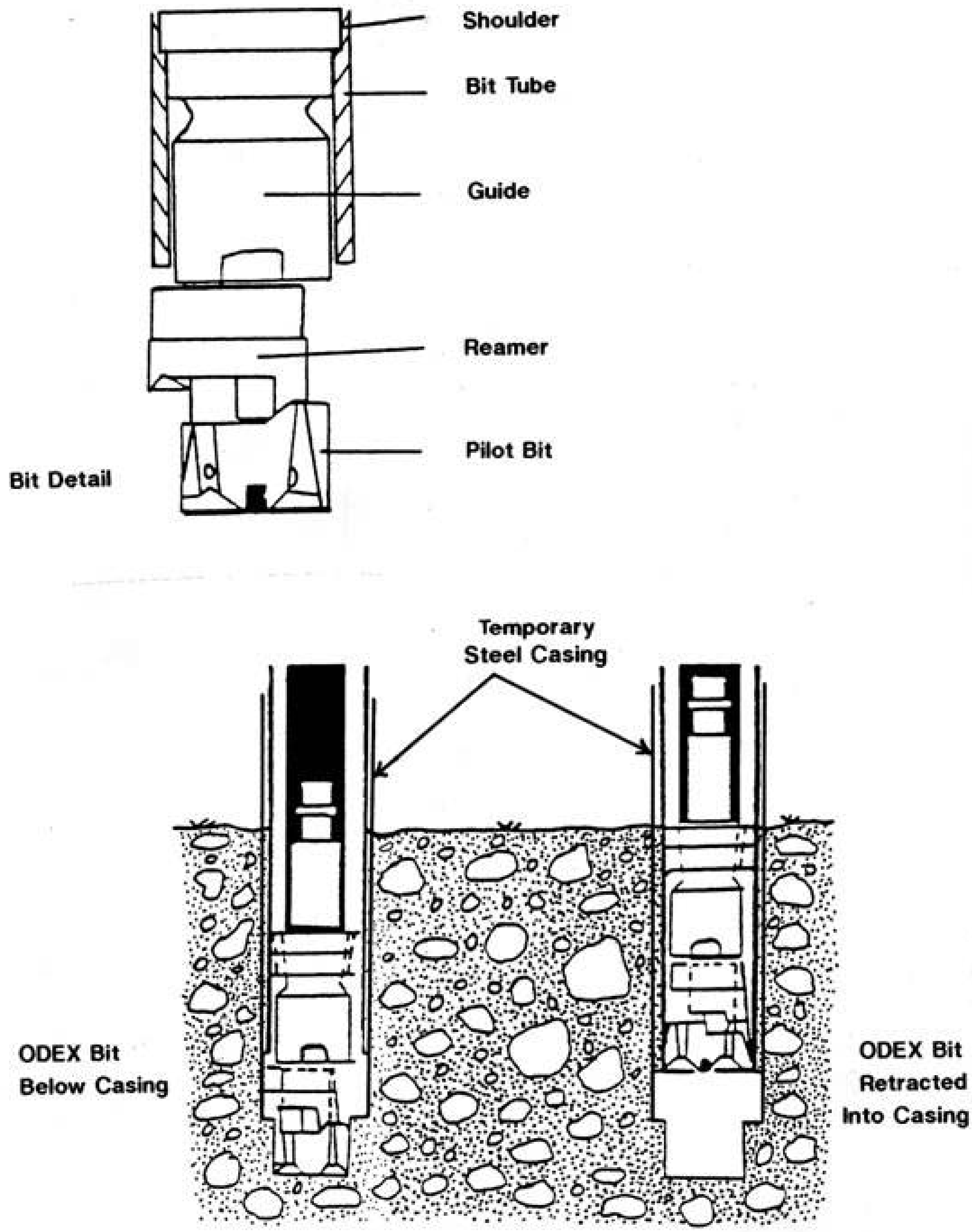


Figure 3.2-12

Schematic of Air Circulation.

Source: After Keely and Boateng (1987)

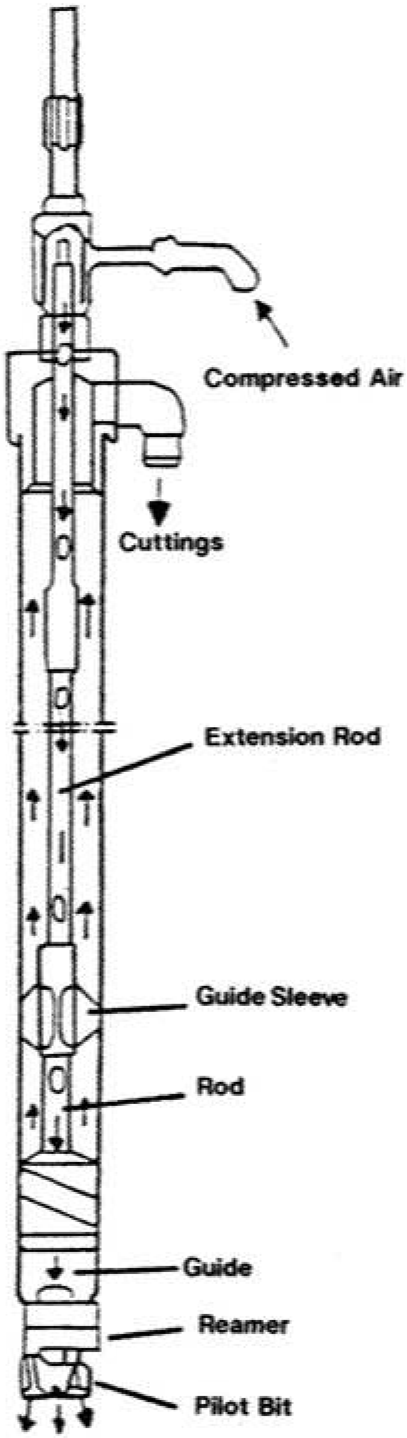


Source: Atlas Copco-Sandrik
Rock Tools (Catalog)

NOT TO SCALE

Figure 3.2-13

Schematic of ODEX Bit.



Source: Atlas Copco-Sandrik
Rock Tools (Catalog)

NOT TO SCALE

Figure 3.2-14

Major Elements of ODEX Drilling System.

Type of Formation	Cable Tool	Direct Rotary (with fluids)	Direct Rotary (with air)	Direct Rotary (Down-the-hole air hammer)	Direct Rotary (Drill-through casing hammer)	Reverse Rotary (with fluids)	Reverse Rotary (Dual Wall)	Hydraulic Percussion	Jetting	Driven	Auger
Dune sand	2	5	Not recommended	Not recommended	6	5*	6	5	5	3	1
Loose sand and gravel	2	5			6	5*	6	5	5	3	1
Quicksand	2	5			6	5*	6	5	5	Not recommended	1
Loose boulders in alluvial fans or glacial drift	3-2	2-1			5	2-1	4	1	1		1
Clay and silt	3	5			5	5	5	3	3		3
Firm shale	5	5			5	5	5	3	Not recommended		2
Sticky shale	3	5			5	3	5	3			2
Brittle shale	5	5			5	5	5	3			Not applicable
Sandstone—poorly cemented	3	4			Not applicable	4	5	4			
Sandstone—well cemented	3	3	5			3	5	3			
Chert nodules	5	3	3			3	3	5			
Limestone	5	5	5	6		5	5	5			
Limestone with chert nodules	5	3	5	6		3	3	5			
Limestone with small cracks or fractures	5	3	5	6		2	5	5			
Limestone, cavernous	5	3-1	2	5		1	5	1			
Dolomite	5	5	5	6		5	5	5			
Basalts, thin layers in sedimentary rocks	5	3	5	6		3	5	5			
Basalts—thick layers	3	3	4	5		3	4	3			
Basalts—highly fractured (lost circulation zones)	3	1	3	3		1	4	1			
Metamorphic rocks	3	3	4	5		3	4	3			
Granite	3	3	5	5		3	4	3			

*Assuming sufficient hydrostatic pressure is available to contain active sand (under high confining pressures)

Rate of Penetration:
1 Impossible
2 Difficult
3 Slow
4 Medium
5 Rapid
6 Very rapid

Source: Driscoll (1986)

Table 3.2-1

Relative Performance of Different Drilling Methods in Various Types of Geologic Formations

Hole Size (in)	Approx. Weight (lb)	Approx. Length	Size Pin (in)	Hole Size (in)	Approx. Weight (lb)	Approx. Length	Size Pin (in)
3	50	4′5″	1¾	8	600	6′6″	4¼ or 4½
3½	75	4′6″	1¾	8	650	7′	4¼ or 4½
4	100	4′10″	2¼ or 2⅝	8	700	7′6″	4¼ or 4½
4½	100	4′	2¼ or 2⅝	8	750	8′	4¼ or 4½
4½	125	5′	2¼ or 2⅝	9	550	6′	3¾ or 4¼
4½	150	6′	2¼ or 2⅝	9	600	6′6″	3¾ or 4¼
5	135	4′	2¼ or 2⅝	9	650	7′	3¾ or 4¼
5	165	5′	2¼ or 2⅝	10	400	4′	3 or 3¼
5	190	5′	2⅝ or 3	10	500	5′	3 or 3¼
5	220	6′	2⅝ or 3	10	450	4′	3½ or 3¾
5	250	7′	2⅝ or 3	10	500	4′5″	3½ or 3¾
5⅝	180	4′	2¼ or 2⅝	10	575	5′	3½ or 3¾
5⅝	200	4′6″	3 or 3¼	10	500	4′	4¼ or 4½
5⅝	220	5′	3 or 3¼	10	625	5′	4¼ or 4½
5⅝	260	6′	3 or 3¼	10	750	6′	4¼ or 4½
6	150	3′4″	2¼ or 2⅝	10	875	7′	4½ or 5
6	175	4′	2¼ or 2⅝	10	950	7′6″	4½ or 5
6	200	4′	3 or 3¼	10	1000	8′	4½ or 5
6	250	5′	3 or 3¼	12	500	3′6″	3½ or 3¾
6	300	6′	3 or 3¼	12	700	4′6″	3½ or 3¾
6¼	270	5′	3 or 3¼	12	800	5′	3½ or 3¾
6¼	320	6′	3 or 3¼	12	600	3′6″	4¼ or 4½
6⅝ – 6¼	300	5′	3½ or 3¾	12	800	4′6″	4¼ or 4½
6⅝ – 6¼	350	6′	3½ or 3¾	12	1000	5′6″	4¼ or 4½
6⅝ – 6¼	400	7′	3½ or 3¾	12½	1100	6′	4½ or 5
6⅝ – 6¼	425	7′6″	3½ or 3¾	12½	1200	6′6″	4½ or 5
6⅝ – 6¼	450	8′	3½ or 3¾	12½	1350	7′	4½ or 5
8	250	3′6″	3 or 3¼	12½	1450	7′6″	4½ or 5
8	300	4′	3 or 3¼	14	800	4′6″	4¼ or 5
8	350	4′6″	3 or 3¼	14	1000	5′	4¼ or 5
8	400	5′	3 or 3¼	15½	1550	6′	4½ or 5
8	400	5′	3½ or 3¾	15½	1700	6′6″	4½ or 5
8	450	5′6″	3½ or 3¾	15½	1850	7′	4½ or 5
8	500	6′	3½ or 3¾	15½	2000	7′6″	4½ or 5
8	600	7′	3½ or 3¾	16	1000	3′6″	4¼ or 5
8	400	4′6″	4¼ or 4½	16	1200	4′6″	4¼ or 5
8	450	5′	4¼ or 4½	16	1700	6′	4¼ or 5
8	500	5′6″	4¼ or 4½	16	2000	7′	4¼ or 5
8	550	6′	4¼ or 4½				

Source: Driscoll (1986)

Table 3.2-2

Dimensions and Weights for Standard Cable Tool Drill Bits (English Units)

Hole Size (mm)	Approx. Weight (kg)	Approx. Length (m)	Size Pin (inches)	Hole Size (mm)	Approx. Weight (kg)	Approx. Length (m)	Size Pin (inches)
76.2	22.7	1.35	1¾	203	272	1.98	4¼ or 4½
88.9	34.0	1.37	1¾	203	295	2.14	4¼ or 4½
102	45.4	1.48	2¼ or 2⅝	203	318	2.29	4¼ or 4½
114	45.4	1.22	2¼ or 2⅝	203	340	2.44	4¼ or 4½
114	56.7	1.52	2¼ or 2⅝	229	250	1.83	3¾ or 4¼
114	68.0	1.83	2¼ or 2⅝	229	272	1.98	3¾ or 4¼
127	61.2	1.22	2¼ or 2⅝	229	295	2.58	3¾ or 4¼
127	74.8	1.52	2¼ or 2⅝	254	181	1.22	3 or 3¼
127	86.2	1.52	2⅝ or 3	254	227	1.52	3 or 3¼
127	99.8	1.83	2⅝ or 3	254	204	1.22	3½ or 3¾
127	113	2.14	2⅝ or 3	254	227	1.35	3½ or 3¾
143	81.6	1.22	2¼ or 2⅝	254	261	1.52	3½ or 3¾
143	90.7	1.37	3 or 3¼	254	227	1.22	4¼ or 4½
143	99.8	1.52	3 or 3¼	254	284	1.52	4¼ or 4½
143	118	1.83	3 or 3¼	254	340	1.83	4¼ or 4½
152	68.0	1.01	2¼ or 2⅝	254	397	2.14	4½ or 5
152	79.4	1.22	2¼ or 2⅝	254	431	2.29	4½ or 5
152	90.7	1.22	3 or 3¼	254	454	2.44	4½ or 5
152	113	1.52	3 or 3¼	305	227	1.07	3½ or 3¾
152	136	1.83	3 or 3¼	305	318	1.37	3½ or 3¾
159	113	1.52	3 or 3¼	305	363	1.52	3½ or 3¾
159	145	1.83	3 or 3¼	305	272	1.07	4¼ or 4½
168 – 159	136	1.52	3½ or 3¾	305	363	1.37	4¼ or 4½
168 – 159	159	1.83	3½ or 3¾	305	454	1.68	4¼ or 4½
168 – 159	181	2.14	3½ or 3¾	318	499	1.83	4½ or 5
168 – 159	193	2.29	3½ or 3¾	318	544	1.98	4½ or 5
168 – 159	204	2.44	3½ or 3¾	318	612	2.14	4½ or 5
203	113	1.07	3 or 3¼	318	494	2.29	4½ or 5
203	136	1.22	3 or 3¼	356	363	1.37	4¼ or 5
203	159	1.37	3 or 3¼	356	454	1.52	4¼ or 5
203	181	1.52	3 or 3¼	394	703	1.83	4½ or 5
203	181	1.52	3½ or 3¾	394	771	1.98	4½ or 5
203	204	1.68	3½ or 3¾	394	839	2.14	4½ or 5
203	227	1.83	3½ or 3¾	394	907	2.29	4½ or 5
203	272	2.14	3½ or 3¾	406	454	1.07	4¼ or 5
203	181	1.37	4¼ or 4½	406	544	1.37	4¼ or 5
203	204	1.52	4¼ or 4½	406	771	1.83	4¼ or 5
203	227	1.68	4¼ or 4½	406	907	2.14	4¼ or 5
203	250	1.83	4¼ or 4½				

Table 3.2-2
(Continued)
Dimensions and Weight for Standard Cable Tool Drill Bits (SI Units)

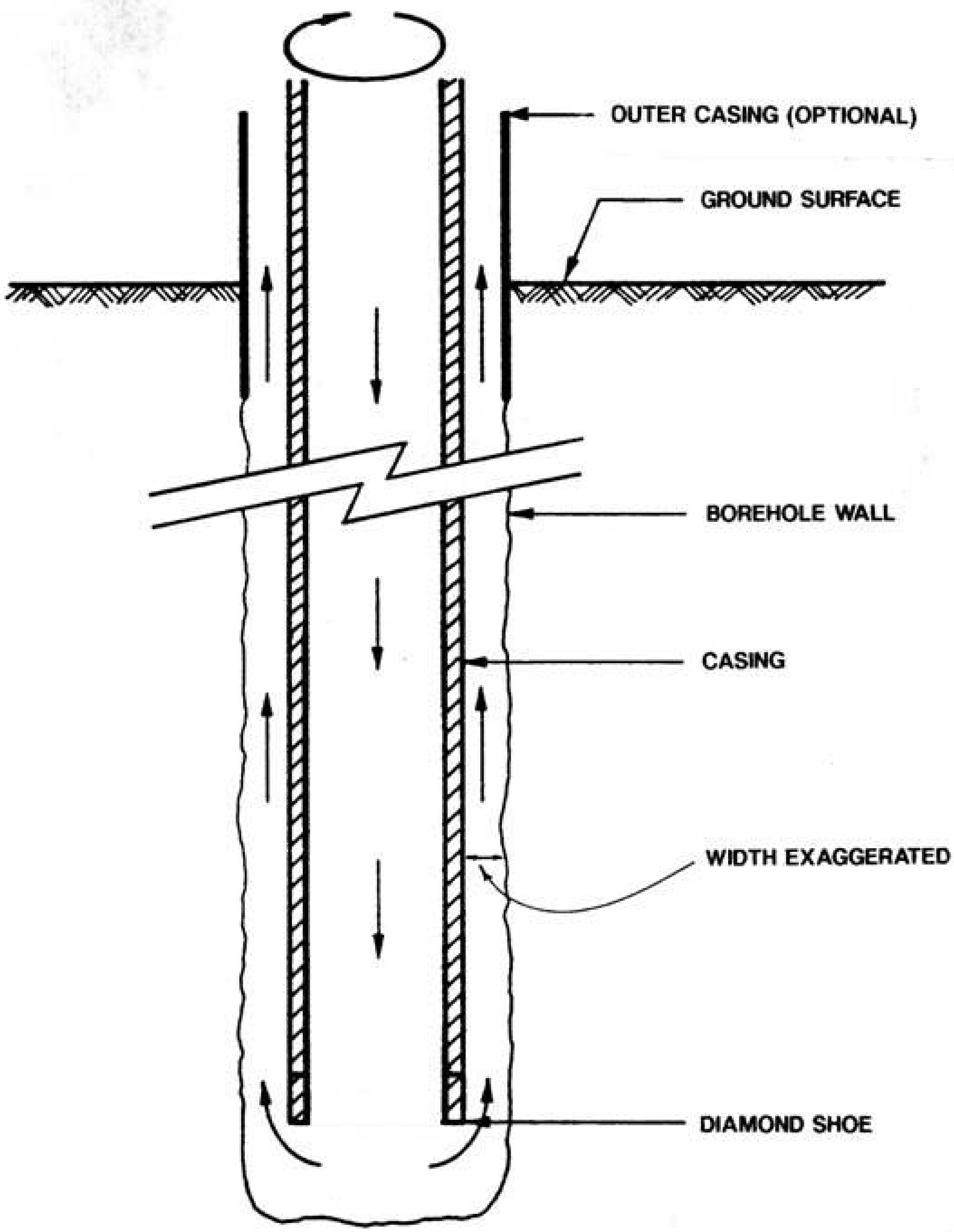
Source: Driscoll (1986)

Diameter in	Diameter mm	Approximate Weight lb	Approximate Weight kg	API Pin Size
2⅞	73.0	4	1.8	N Rod
2 15/16	74.6	4¼	1.9	N Rod
3⅛	79.4	4¼	1.9	N Rod
3½	88.9	7	3.2	2⅜ N Rod
3¾	95.3	7½	3.4	2⅜
3⅞	98.4	7½	3.4	2⅜
4¼	108	10	4.5	2⅜
4½	114	11	5.0	2⅜
4¾	121	13	5.9	2⅞
5	127	17	7.7	2⅞
5⅛	130	19	8.6	2⅞
5⅝	143	22	10.0	3½
6	152	27	12.2	3½
6¼	159	30	13.6	3½
6¾	171	33	15.0	3½
7⅜	187	42	19.1	3½
7⅝ – 7⅞	200	52	23.6	4½
8½	216	75	34.0	4½
8¾	222	75	34.0	4½
9	229	75	34.0	4½
9⅝	244	105	47.6	6⅝
9⅞	251	115	52.2	6⅝
10⅝	270	120	54.4	6⅝
11	279	145	65.8	6⅝
12¼	311	175	79.4	6⅝
13¾	349	219	99.3	6⅝
14¾	375	360	163.3	6⅝
15	381	375	170.1	6⅝ or 7⅝
16	406	450	204.1	6⅝ or 7⅝
17½	445	575	260.8	6⅝ or 7⅝
18½	470	625	283.5	6⅝ or 7⅝
20	508	665	301.6	6⅝ or 7⅝
22	559	810	367.4	6⅝ or 7⅝
24	610	1,014	460.0	6⅝ or 7⅝
26	660	1,217	552.0	6⅝ or 7⅝
30	762	2,320	1,052.35	7⅝ or 8⅝

Table 3.2-3

Source: Driscoll (1986)

Sizes and Weights for Tricone Roller Bits



NOT TO SCALE

Source: MADEP

Figure 3.2-4

Schematic of Spun Casing Drilling Method.

Size	OD		ID		Weight		Coupling OD	
	in	mm	in	mm	lb/ft	kg/m	in	mm
DRILL RODS—FLUSH COUPLED								
E†	1 5/16	33.3	7/8	22.2	2.7	4.0	7/16	11.1
A†	1 5/8	41.3	1 1/8	28.5	3.7	5.7	9/16	14.3
B†	1 7/8	47.6	1 1/4	31.7	5.0	7.0	5/8	15.9
N†	2 3/8	60.3	2	50.8	5.2	7.5	1	29.4
EW‡	1 3/8	34.9	15/16	23.8	3.1	4.7	7/16	11.1
AW‡	1 3/4	44.4	1 1/4	31.8	4.2	6.5	5/8	15.9
BW‡	2 1/8	54.0	1 3/4	44.5	4.3	6.7	3/4	19.3
NW‡	2 5/8	66.7	2 1/4	57.1	5.5	8.4	1 3/8	34.9
HW‡	3 1/2	88.9	3 1/16	77.8	7.7	11.5	2 3/8	60.3
CASING—FLUSH JOINTED								
EW	1 13/16	43.0	1 1/2	38.1	2.76	4.2		
AW	2 1/4	57.2	1 29/32	48.4	3.80	5.8		
BW	2 7/8	73.9	2 3/8	60.3	7.00	10.6		
NW	3 1/2	88.9	3	76.2	8.69	13.2		
HW	4 1/2	114.3	4	101.6	11.35	16.9		
PW	5 1/2	139.7	4 7/8	127.0	15.35	22.8		
SW	6 5/8	168.3	6 1/32	152.4	19.49	29.0		
UW	7 5/8	193.7	7	177.8	23.47	34.9		
ZW	8 5/8	219.1	8 3/32	203.2	27.80	41.4		
CASING—FLUSH COUPLED								
EX	1 13/16	46.0	1 5/8	41.3	1.80	2.7	1 1/2	33.1
AX	2 1/4	57.2	2	50.8	2.90	4.4	1 29/32	48.4
BX	2 7/8	73.0	2 9/16	65.1	5.90	8.8	2 3/4	69.3
NX	3 1/2	83.9	5 3/16	81.0	7.80	11.8	3	76.2
HX	4 1/2	114.3	4 1/8	104.8	8.65	13.6	3 15/16	100.0

CASING—STANDARD DRIVE PIPE

Size in.	OD		ID		Weight		Coupling OD	
	in	mm	in	mm	lb/ft	kg/m	in	mm
2	2 3/8	60.3	2 1/16	52.4	5.5	8.3	2 7/8	73.0
2 1/2	2 7/8	73.0	2 15/32	62.7	9.0	13.6	3 3/8	85.7
3	3 1/2	88.9	3 1/16	77.8	11.5	17.4	4	101.6
3 1/2	4	101.6	3 9/16	90.5	15.5	23.4	4 5/8	117.3
4	4 1/2	114.3	4 1/32	102.4	18.0	27.2	5 3/16	131.8
CASING—EXTRA HEAVY DRIVE PIPE								
2	2 3/8	60.3	1 15/16	49.2	5.0	7.6	2 7/32	56.4
2 1/2	2 7/8	73.0	2 21/64	59.1	7.7	11.6	2 5/8	66.7
3	3 1/2	88.9	2 29/32	73.8	10.2	15.4	3 1/4	82.5
3 1/2	4	101.6	3 23/64	85.3	12.5	18.9	3 3/4	95.3
4	4 1/2	114.3	3 53/64	97.2	15.0	22.7	4 1/4	107.8

*From Diamond Core Drill Manufacturers Association (DCDMA).

†Original diamond core drill tool designations.

‡Current DCDMA standards.

Table 3.2-5

Source: Hunt (1984)

Standard Sizes of Casing and Tools

(a) Recommended Rotating Speeds for all Sizes and Types of Bits in Various Formations

Bit Sizes and Types	Sticky Shales or Gumbos	Soft Unconsolidated Shales, Silts, Sandy Shales, etc.	Medium Hard Shales, Sandy Shales, Soft Chalk	Medium Hard Sandstones Hard Very Sandy Shale	Very Hard Sandstones, Quartzite, Angular Limestones, Anhydrite	Hard Brittle Shale and Limestone Conchoidal Fracture
13 to 20 Inch						
Drag	100 – 130	100 – 130				
Zublin	100 – 160	100 – 150	100 – 175	125 – 175		
Rock (Rolling Cutter)		125 – 200	100 – 200	60 – 125	40 – 60	40 – 150
10 to 13 Inch						
Drag	100 – 175	100 – 300				
Disc		110 – 180				
Zublin	125 – 175	125 – 200	125 – 200	125 – 200		
Rock (Rolling Cutter)		150 – 300	100 – 250	80 – 120	40 – 80	60 – 150
6 to 10 Inch						
Drag	125 – 200	100 – 200				
Zublin	150 – 200	100 – 150	150 – 225	150 – 200		
Rock (Rolling Cutter)		150 – 300	100 – 250	80 – 125	40 – 100	60 – 200

The minimum speeds given are for flat lying strata and certain type bits. The maximum speeds are for flat or inclined formations. The maximum allowable weight may be carried in flat beds and the minimum in steeply dipping strata. Slower and faster speeds than these recommended are useful in specific and more or less unusual cases.

(b) Weight on Bit and Rotary Speed in Various Formations

Bit Classification	Weight per in (2.54 cm) of Bit Diameter lb/in	Weight per in (2.54 cm) of Bit Diameter kg/cm	Rotary Speed rpm
Soft formation	3,400 to 6,750 4,050 to 7,800	609 to 1,210 725 to 1,400	250 to 100 180 to 60
Medium formation	4,500 to 9,000	806 to 1,610	120 to 40
Hard milled tooth bit	5,600 to 11,250	1,000 to 2,010	70 to 35
Hard insert bit	2,250 to 5,600 4,500 to 9,000	403 to 1,000 806 to 1,610	70 to 35 65 to 35
Hard friction bearing bit	4,500 to 6,750	806 to 1,210	60 to 35

Table 3.2-6

Rotary Bits

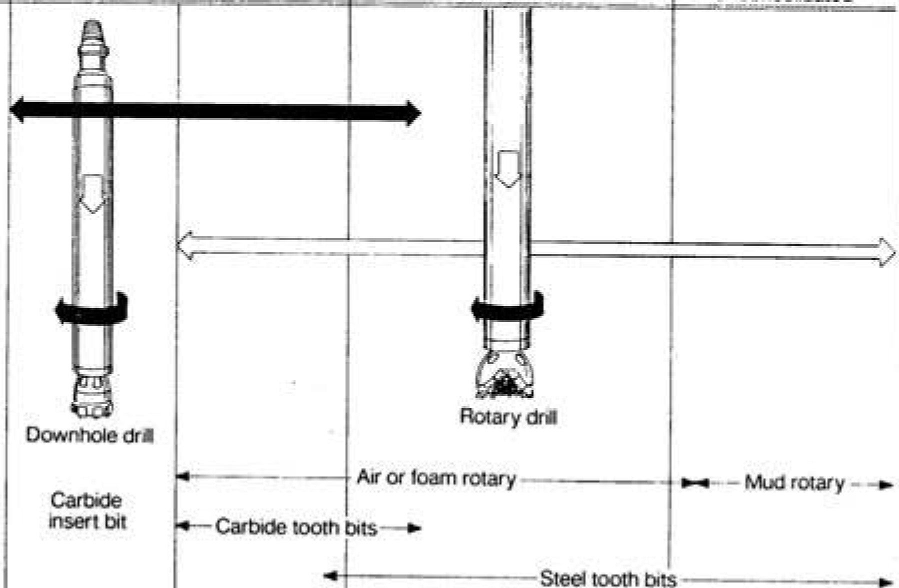
Source: Driscoll (1986)

WELL DRILLING SELECTION GUIDE

Type of Formation

Geologic Origin ►	Igneous and Metamorphic	Sedimentary	
Examples ►	Granite Quartzite Basalt Gneiss Schist	Limestone Sandstone Shale	Clay Sand Gravel
Hardness ►	Very hard to hard	Hard to soft	Unconsolidated

Drilling Methods



Diameter	Small (4 - 8 in)	Small to medium (6 - 12 in)
Depth	Shallow (50 - 200 ft)	Shallow to deep (50 - 1,000 ft)

Source: Driscoll (1986)

Table 3.2-7

Guide for the Use of Bit Types in Air Drilling Systems

APPENDICES

Appendix	Title	Page No.
A-1	Example # 1 of a Boring Log	55
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A-3	Example # 3 of a Boring Log	57

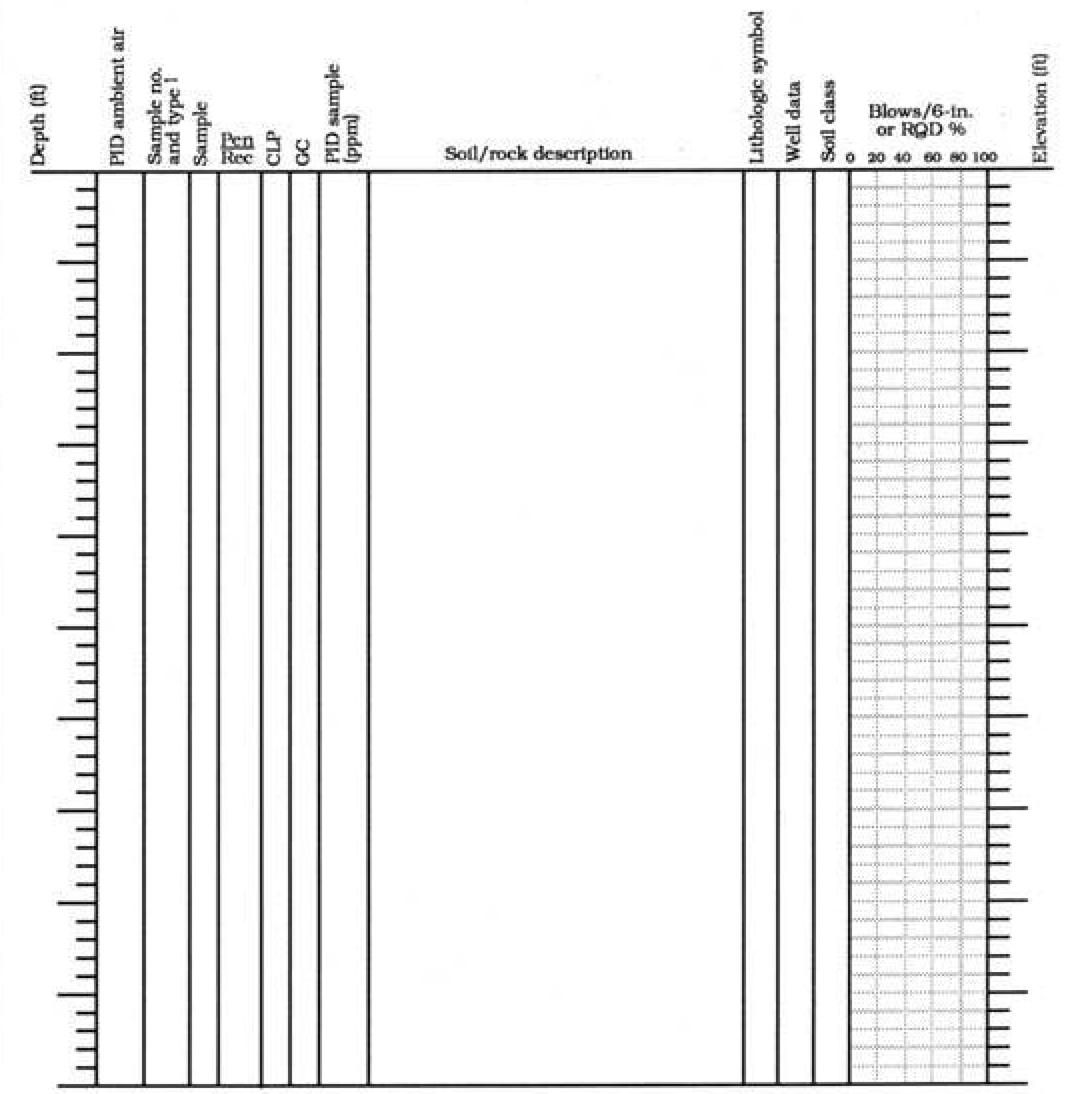
Note: These are variations of the same theme. Each one has certain advantages which are not related to a specific drilling technique.

A-1: This log visually shows blows/6-in and is particularly useful if extensive sampling for analysis will take place.

A-2: This log is useful if comments are important and Lower Explosive Limit (LEL) readings will be taken.

A-3: This log is preferred if multiple changes in geology are expected as there is plenty of room for descriptions.

			Boring no:
Client			Project no:
Contractor		Date started	Completed
Method	Casing size	PID	Protect'n level
Ground el.	Soil drilled	Rock drilled	▽ Below grnd
Logged by	Ch'd by	Date	Site



[1] U = Thin wall tube S = Split spoon R = Rock

Source: ABB-ES

Figure A-1

Example No. 1 Boring Log.

			Boring no:
Project no.	Project name		Page of
Contractor	Driller	Date started	Completed
Method	Casing size	PID	Protect'n level
Ground el.	Soil drilled	Rock Drilled	Total depth
Logged by	Ch'd by	Date	▽ Below grnd

Sample No.	Depth in feet	Blows per 6 inches	Pen / Rec	Description	HNU JAR	Comments on Advance of Boring	Monit'g HNU	Monit'g LEL

Source: ABB-ES

Figure A-2

Example No. 2 Boring Log.

Date
Started ______
Finished ______
Sheet ______ of ______

Hole No. ______
Surf. Elev. ______
G. W. Depth ______

Project ______
______

Location ______
Method of Investigation ______

Depth (ft)	Samples	Sample No.	Blows on Sampler 0/6	6/12	12/18	N	Blow on Casing C	Soil or Rock Classification	Notes

N = No. blows to drive ______ "spoon ______ "with ______ lb. pin wt. falling ______ "per blow.
C = No blows to drive ______ "casing ______ "with ______ lb. weight falling ______ "per blow.

Classification ______
______

Source: ABB-ES

Figure A-3

Example No. 3 Boring Log.

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SECTION 3.3 BORINGS IN CONTAMINATED AREAS

SECTION 3.3
BORINGS IN CONTAMINATED AREAS

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3.3 SECTION
BORINGS IN CONTAMINATED AREAS

3.3-1 PURPOSE

A fundamental aspect of most contamination investigations is the delineation of the extent of contamination in soil materials and ground water. Typically, both the horizontal (areal) extent and vertical distribution of the contamination must be defined. Geologic heterogeneities, variations in hydraulic conductivity, and contaminant characteristics will significantly influence the subsurface distribution of the contaminants. Accurate evaluation of contaminant migration and distribution requires the isolation and sampling of specific zones within an aquifer. To ensure the collection of representative samples and to prevent cross-contamination of soils and ground water, special drilling techniques may be required. In some cases, additional precautions must be taken during drilling to prevent contamination of nearby existing or potential water supplies. Protection of the health and safety of workers at contaminated waste sites is discussed in Section 2.3 Health and Safety Plans.

For the purpose of this discussion, "contaminated areas" are defined as highly contaminated source areas (i.e., oil and hazardous materials spills, landfills, waste lagoons, or zones of highly contaminated ground water). The contamination may occur in either the saturated or unsaturated zones or both, depending on the location of the source and length of time the leakage has been taking place. In these areas drilling may alter or mask the existing distribution of contaminants by bridging contamination between aquifers. Some drilling techniques are better suited than others for investigations in contaminated areas. Generally, mud-rotary and air-rotary techniques are undesirable drilling methods in contaminated areas, due to the problem of inadequate control of fluids and cuttings in the borehole and at the surface (see Section 3.2). The most suitable drilling methods for contaminated areas employ casing, either single or multiple, to seal off the overlying strata during drilling. The basic considerations for selecting an appropriate drilling method at contaminated sites are, as follows:

- To prevent cross-contamination or migration of contaminants in the borehole.

- To obtain accurate and representative samples of formation materials and contaminants.

- To introduce a minimum amount of water or fluid into the aquifer, preferably none at all.

- To produce a borehole that does not pose a potential contamination migration pathway when a monitoring well is installed.

- To minimize the safety hazards to the drilling crew, field personnel, workers at and residents of abutting properties.

3.3-2 RECOMMENDED DRILLING METHODS

Because each site is unique in terms of geologic material, ground water characteristics, and types and properties of potential contaminants, the development of the subsurface exploration program may require modification of standard, generally accepted, drilling methods. It is always advisable to plan a drilling program, so that the drilling sequence progresses from the cleaner areas to the more contaminated areas. The drilling methods most generally recommended for application in contaminated subsurface conditions are briefly described in the following subsections.

3.3-2.1 Telescoping Casing

Perhaps the most common method used to prevent cross-contamination in a borehole during drilling is telescoping a smaller casing inside a larger one that has been terminated at some distance below a contaminated zone or at an impervious stratum. Several drilling methods can be used to complete telescoped, multi-cased wells. These methods include cable tool, hollow-stem augers, drive-and-wash, and spun casing. In some situations, where the sampling of overlying contamination is not of interest, mud or air-rotary techniques might be used with prior approval from DEP.

Telescoping methods may use either a temporary or permanent casing. The telescoped casing method requires drilling a relatively large-diameter borehole, installing a temporary casing, and sealing that casing with a bentonite cement mixture. Once the temporary casing is installed and sealed, a second, smaller-diameter casing is set inside the first casing and drilling proceeds from the bottom of the temporary casing through the seal to the desired depth. Casing may be "telescoped" two or three times depending on the number of contaminated zones encountered and the size of the casings. When the boring has been completed to the desired depth, drilling stops. Depending on the site-specific project specifications, the borehole may either be plugged and the casing removed from the hole, or the borehole may be used for the installation of a monitoring well before the casing is pulled. Plugging of boreholes is described in Section 3.9 of these Standard References; well installation is addressed in Section 4.3.

In some applications (e.g., highly contaminated zones above an aquifer that serves as a water supply), initial installation of a permanent casing is preferable. This is a more expensive method, due to the cost of the permanent casing and the time required for installation. As shown in Figure 3.3-1, this method requires a series of steps. First, a pilot hole is drilled to the desired depth, filled with grout, and a permanent casing is installed, as shown in Step 1. In this technique, the pilot hole has a diameter larger than the permanent casing. Once the grout has set up, a second casing is advanced by drilling through the grout plug on the inside of the permanent casing and continuing with the drilling as shown in Step 2 (Figure 3.3-1). As the second casing is removed, the well riser is sealed with grout to the surface. This method produces a double seal through the highly contaminated zone at the surface and into the impervious stratum.

Advantages

- o It is the best technique for minimizing cross contamination.
- o Method is the least expensive technique as the casing is pulled.
- o Multiple casings can be utilized in difficult geological settings.
- o Multiple casings combined with seals provide the best protection against cross contamination.

Disadvantages

- o Method can be expensive if permanent casing into bedrock is left in the ground.
- o Inner casing may jam or bridge inside of outer casing.
- o Casings can be difficult to pull if set at a depth.
- o Casings can be difficult to separate from each other.

3.3-2.2 Hollow-stem Auger/Flush-joint Casing

A combination of hollow-stem augers and flush-joint casing can also be used to complete a boring where the contaminated sources occur above the water table. Large-diameter (i.e., 6- to 8-inch ID) hollow-stem augers can be used to advance the borehole to the top of the water table, or the boundary between the contaminated/clean horizon (as determined by field screening), or to the top of an impervious stratum above the water table.

The borehole would then be advanced beyond this depth with flush-joint casing (i.e., 4-, 5-, or 6-inch OD) that is placed inside the hollow-stem augers. The flush-joint casing can be advanced with standard drive-and-wash techniques. Standard soil samples can be obtained with either method. A schematic of this drilling method is presented in Figure 3.3-3. It is recommended that (1) all casing be flush-joint, threaded steel; and (2) that the flush-joint casing should be driven through the remaining portion of the impervious strata to minimize the potential for cross-contamination. If spun technique is required, a second telescope can be placed inside the driven casing.

In this drilling method, the augers would not penetrate below the contaminated zone, except to reach the top of an impervious stratum above the water table. Therefore (1) the contaminants would not be smeared or dragged down or up by the augers, and (2) monitoring well installations would not be compromised by the auger methodology. Installation of telescoped casing inside a hollow-stem auger has the following advantages and disadvantages:

Advantages

- o Water would not be required near highly contaminated surface zones.
- o Casing can be spun into bedrock, if desired.
- o Contaminated zones at greater depths can be isolated by additional telescoping of flush-joint casing.
- o Standard soil samples can be collected.

Disadvantages

- o Inner casing may jam or bridge inside augers.
- o Introduction of water during drilling is required when using inner casings.

3.3-3 DISPOSAL OF DRILLING SPOILS

Another significant consideration when drilling in contaminated areas is the disposal of drilling spoils that may include water as well as soil. Efforts should be made to minimize the amount of material that is removed from the contaminated area and the amount of equipment or water that comes in contact with the contaminants. If a site is highly contaminated, drill cuttings and fluids must be containerized, screened for chemical contaminants, and, in some cases, manifested as hazardous waste. In designing a drilling program for a suspected or known oil or hazardous material disposal site, consideration should always be given to minimizing the amount of waste material produced, as its disposal can result in logistical problems during drilling and substantial costs for disposal. For these reasons, auger or casing techniques are often preferred over drive-and-wash techniques because liquid drilling spoils are more difficult to contain.

3.3-4 DECONTAMINATION OF EQUIPMENT

Decontamination of equipment used to collect samples is essential in order to maintain the integrity of the chemical data from different sampling locations. In general, decontamination should provide for adequate cleaning of the drilling and sampling tools for the particular contaminants found at a specific site. Different chemicals or mixtures of chemicals will require the use of different cleaning methods or compounds.

The method or compounds selected for decontamination should fully remove site contaminants from the sampling equipment without interfering with the specific chemical analysis for that site. The method of choice should also consider the site and weather constraints.

In general, decontamination usually is a sequential procedure beginning with a water rinse, detergent wash/steam cleaning, solvent and/or acid/base wash and final deionized or potable water rinse. If wash/rinse steps are conducted in containers (i.e., buckets, drums, etc.), the solutions should be changed between each boring or sample location to prevent cross-contamination. Based on the anticipated contaminants at a specific site, the choice of decontamination methods and compounds may consist of the following:

- o Potable water rinse.
- o Detergent (i.e., liqui-nox which is biodegradable or Alconox which is biodegradable and phosphate-free) wash followed by potable or distilled water rinse.
- o Steam cleaning.
- o Low strength organic solvent (i.e., methanol/ethanol/alcohol) wash followed by water rinse.
- o High strength organic solvent (i.e., hexane/freon) wash followed by water rinse.*
- o Common petroleum product (i.e., fuel oils, kerosene, gasoline) wash followed by detergent wash and water rinse.*
- o Acid/base wash followed by water rinse.

*Decontamination solutions require special handling.

More than one method or compound may be used in series for a particular site. Section 6.5 of the Standard References describes the choice of decontamination methods in terms of the required test parameters. In extreme cases, disposable equipment is recommended over decontamination because the level of effort and costs required to adequately clean the equipment and dispose of the decontamination solutions may not be warranted.

3.3-4.1 Cleaning the Drill Rig

All drilling equipment should be decontaminated prior to arriving at the site. An inspection of the equipment should be made prior to moving onto the site. It is essential that all parts of the drill pipe, drive head, tracks, or wheels be thoroughly cleaned at the site before starting work. The drill rig and attached equipment should be thoroughly steam-cleaned between contaminated borings. If necessary, the equipment should be scrubbed to loosen packed-on materials. Those parts of the drill rig that do not come in contact with the well installation or sampling equipment should be cleaned as necessary between borings. Vehicle wheels and tracks should be checked and cleaned between borings to prevent the spreading of contaminated soil and liquid around the site. At the completion of the exploration program, the drill rig and attached equipment should be decontaminated prior to leaving the site.

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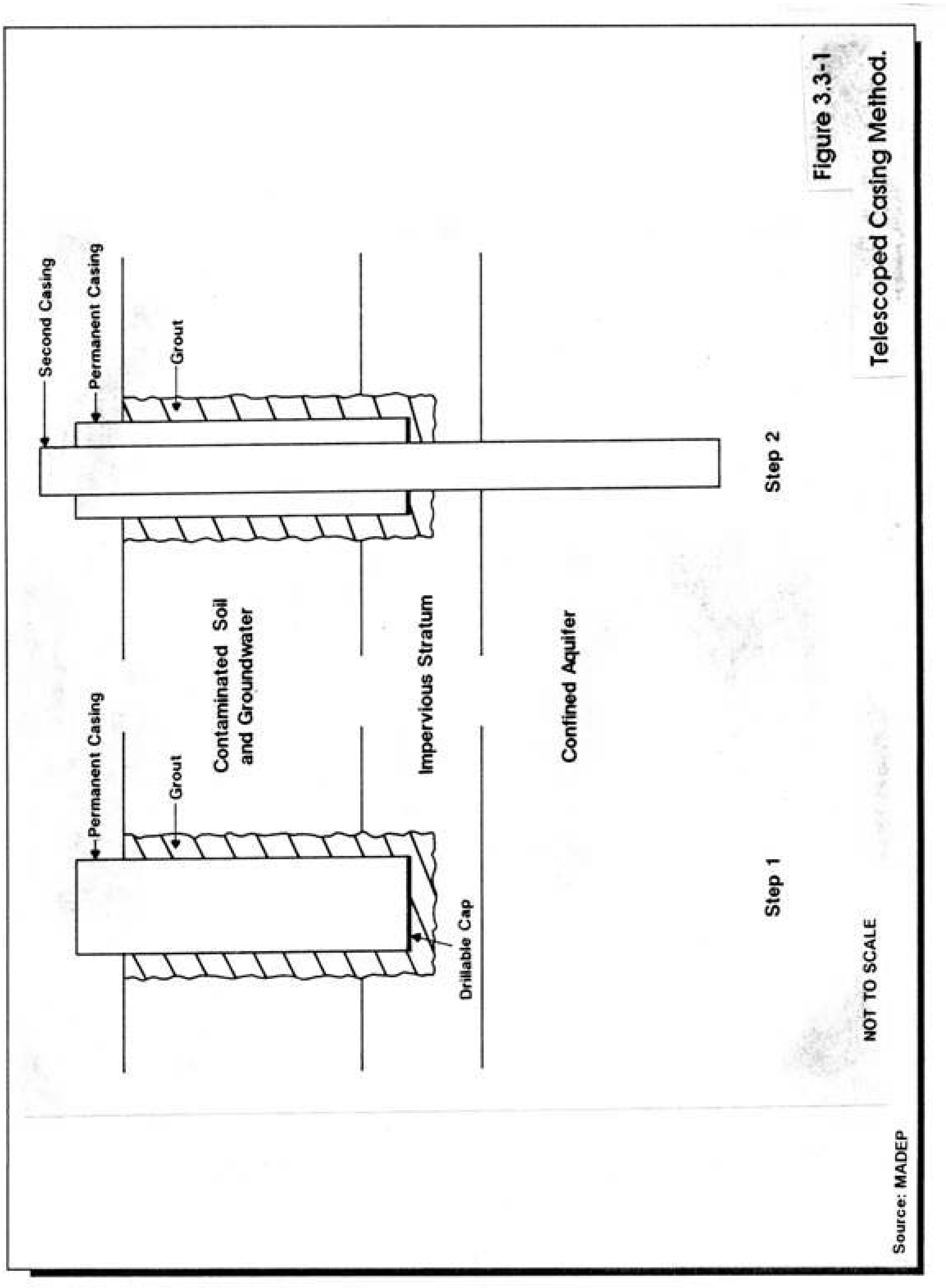
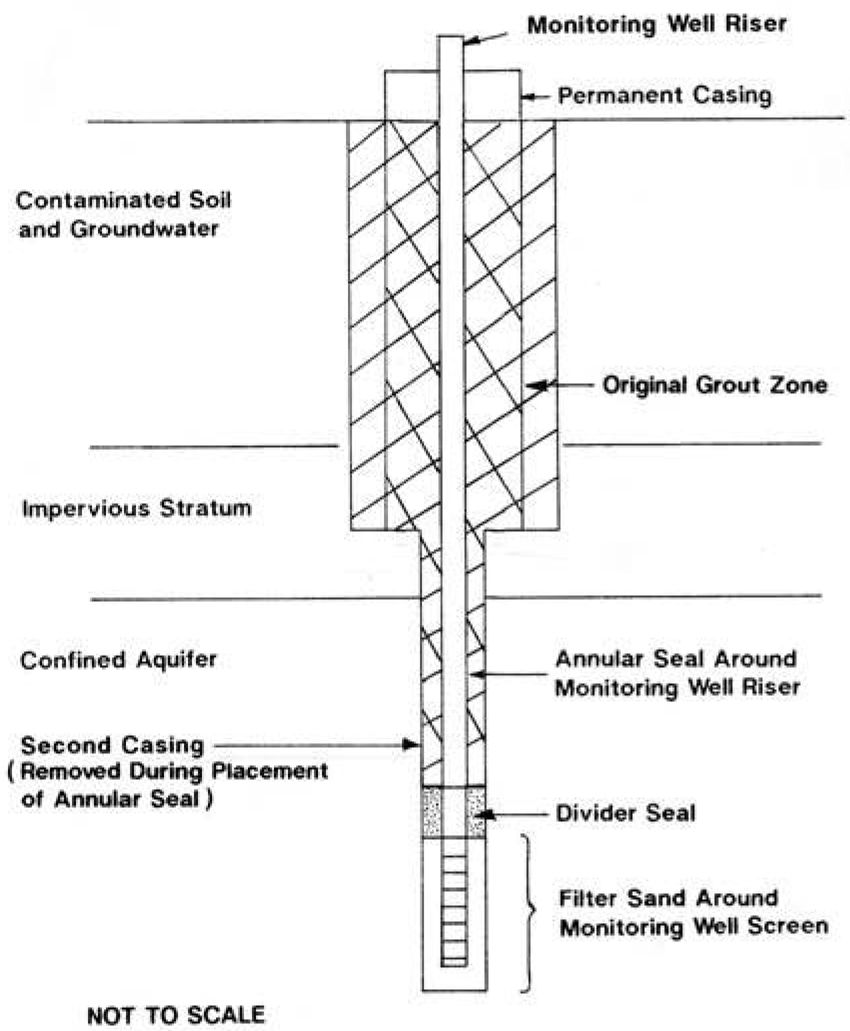


Figure 3.3-1
Telescoped Casing Method.



Source: MADEP

Figure 3.3-2

Monitoring Well Installed with Telescoped Casing Method.

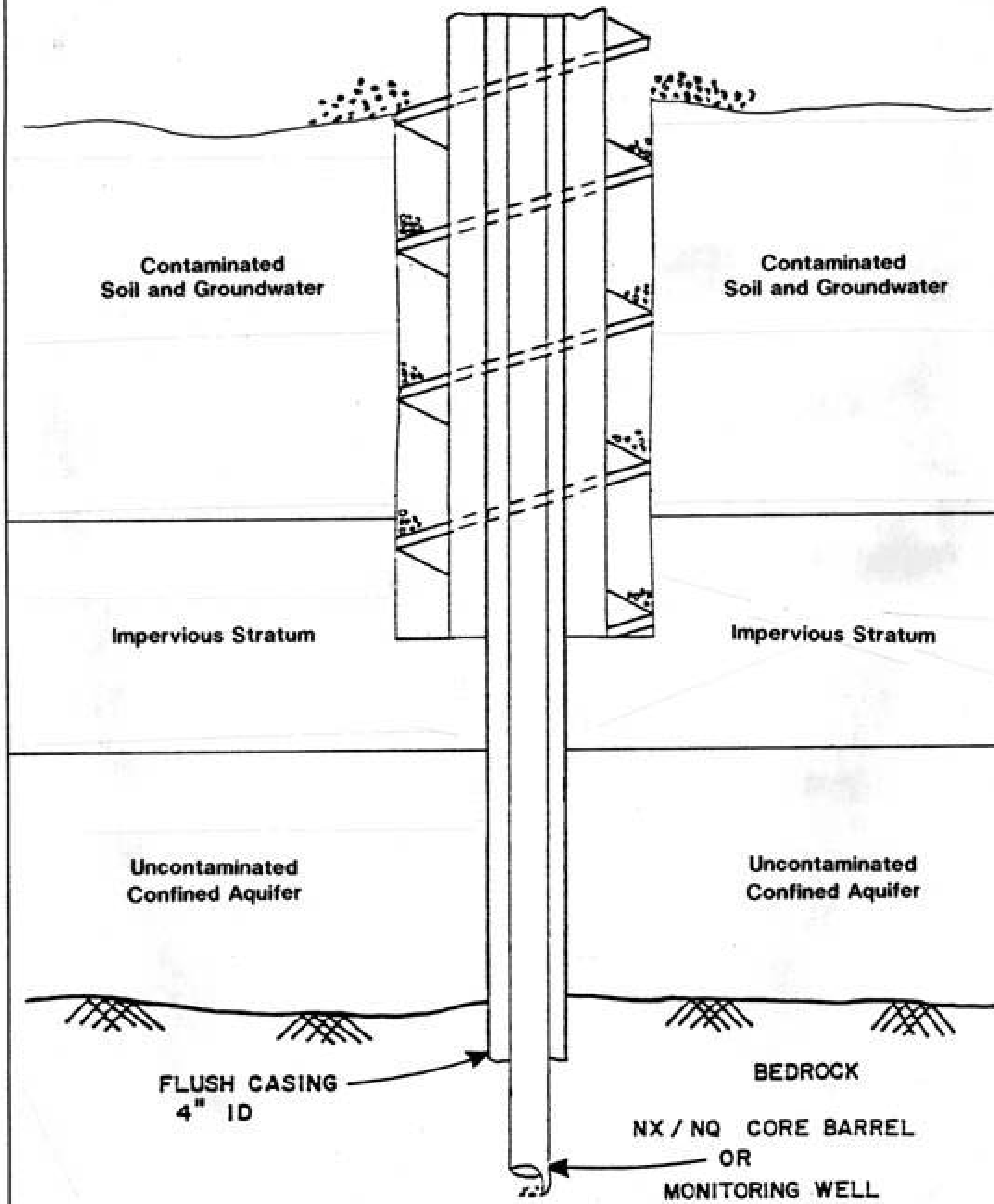


Figure 3.3-3

Source: MADEP

Contaminated Borings - Drilling with Hollow-stem Augers/Flush-joint Casing.

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3.4 IN SITU SAMPLING OF SOIL

3.4-1 PURPOSE

Considerable variability exists in methods used to obtain soil samples by both different individuals and by a single individual, particularly when an established procedure is not available for reference. The purpose of this Standard Reference (SR) is to provide methods and procedures for the collection of soil samples that will reduce variability and encourage continuity in sample collection protocols by samplers.

Soil is a natural unconsolidated aggregate of mineral grains that is formed as the result of chemical and physical weathering of consolidated rock formations. It is sampled to obtain a specimen (disturbed or undisturbed) that is representative of a particular subsurface stratum. It can be sampled for chemical analysis, geotechnical analyses, and geologic classification. Selection of a specific sampling technique is dependent on the objectives of the environmental assessment. For example, while some projects may require a detailed sampling program to quantify a deep source of contamination, other projects may require characterization of only the uppermost surficial soils for clean-up of a recent spill. Characterization of extensive contamination may require collection of samples from multiple depths. The selection of site-specific soil sampling techniques may be influenced by one or more of the following factors:

- Purpose of exploration.
- Depth of soil to be sampled.
- Anticipated subsurface soil types and conditions.
- Engineering properties to be determined.
- Depth to the water table.
- Degree and types of contamination anticipated, if any.

Once the method of exploration (e.g., test pit, boring, or hand auger) has been determined, the sampling methodology required to provide appropriate specimens for analyses should be selected. Soil sample methodologies fall in to two broad categories:

- Disturbed Samples
- Undisturbed Samples

This SR describes sampling devices and procedures for the collection of both disturbed and undisturbed samples at sites that are presumed to be either uncontaminated or contaminated. It has become an increasingly accepted field procedure at contaminated sites to screen soil samples with a photoionization detector (PID) to check for the presence of volatile organics. While many sampling devices are available to collect soil samples, this section provides SRs only for those devices most commonly used in environmental assessment work. Other devices, traditionally used for geotechnical engineering studies, are only listed here. SRs for engineering studies are outside the scope of this section and are not included.

For the purpose of conducting environmental testing, the following factors should be considered in selecting the sampling method:

- Representativeness
- Sample suitability for selected analysis
- Ease of operations
- Flexibility
- Practicality
- Safety
- Budget
- Requirement for decontamination

The significance of these factors will be determined by the purpose and objective(s) of the sampling plan and the type of environmental assessment to be conducted.

The following sections describe various methods and equipment used to obtain representative samples and some of the constraints upon their use. Decontamination of sampling equipment is not included in this section; it is discussed in Section 2.3 and 6.0.

3.4-2 DISTURBED SAMPLES

A disturbed sample is a representative sample of a selected geologic unit that has undergone structural alteration as a result of the sampling operation. These types of samples can be used for soil classification, soil index testing, and analytical testing purposes. Disturbed samples obtained from borehole cuttings may not be representative of in-place strata and, therefore, are only suitable for general lithologic identification.

Soil samples may be either discrete or composite. A discrete sample represents a single location within the soil column; it must be used for all volatile organic analyses. A composite sample represents a mixture of soil from more than one discrete location. If a composite sample is to be obtained, it can be mixed in a shallow high density polyethylene pan, lined with aluminum foil, or in a stainless steel pan. Stainless steel sieves may be used to remove larger rock fragments (see Figure 3.4-1). Such compositing procedures are not appropriate for samples obtained for analysis for volatile organic compounds because the agitation of the sample results in a loss of volatiles from the sample.

Soil sampling devices used to collect disturbed samples are separated into two groups, differentiated by the depth of sampling:

- Surface and shallow subsurface soil sampling
- Borehole soil sampling

3.4-2.1 Surface and Shallow Subsurface Soil Sampling

Surface and shallow subsurface soil sampling is generally done using manually operated sampling equipment. Depending on the subsurface conditions, this method is limited to approximately 20 feet of the soil. In some cases backhoes can be used to make excavations to depths of more than 20 feet. Soil sampling devices and equipment that can be used to obtain surface and shallow subsurface soil samples include:

- Cleaned or disposable scoops, hand trowels, and shovels
- Slotted sampling trier
- Hand auger
- Backhoe buckets
- Plastic syringes

3.4-2.1.1 Scoops, Hand Trowels, and Shovels

The practical sample depth of scoops, hand trowels and shovels ranges from the surface to about two feet.

(a) Advantages

- Ease of use.
- Easy to decontaminate.
- An inexpensive method to collect samples at or near the ground surface.

(b) Disadvantages

- Limited depth of sampling.
- Difficult or impossible to use in frozen ground.
- Difficult in gravelly soil.

(c) Procedures for Use

(1) Carefully remove the top layer of soil to the desired sample depth with a clean tool.

(2) If applicable, screen the area to be sampled using a organic vapor analyzer and record readings in the field log. The PID screen is used as a field safety procedure as well as for selecting potentially contaminated soil samples.

The soil readings should be compared to action levels presented in the project Health and Safety Plan (see Section 2.3). The operator of the PID must be experienced in its use and aware of the effect of factors such as temperature, humidity, or methane affecting the instrument readings.

(3) Using a clean tool, remove and discard a thin layer of soil from the area that came in contact with the shovel.

(4) Obtain a discrete soil sample using a stainless steel lab spoon or its equivalent. Place the sample into a sterile wide-mouth glass soil sample jar with screw on cap. In addition to analytical samples, a reference sample considered representative of the soil may also be collected and stored in a glass jar for future use.

(5) Check that a teflon liner is present in the cap of all analytical sample jars, if required. Secure the cap tightly. Although chemical preservation of solids is generally not required, the samples should be refrigerated and analyzed within specified holding times.

(6) Label the sample bottle with the appropriate sample tag. Be sure to label the tag carefully and clearly using indelible ink. Complete all chain-of-custody documents and record in the field log book. Use of pre-labelled bottles aids greatly, particularly if gloves are being worn or weather conditions are adverse.

(7) Decontaminate equipment after use and between sample locations. Also decontaminate sample containers and/or isolate them (such as sealing in Ziploc bags).

3.4-2.1.2 Soil Sampling Tube

This sampler is useful within a depth range of two and one-half to three feet, depending upon soil conditions. Samplers range in diameter from one to two inches. A soil sampling tube allows for visual inspection of the specimen or screening with a PID before it is placed into a sample container. An example of a soil sampling tube is shown on Figure 3.4-2.

(a) Advantages

- Ease of use.
- Limited disturbance of ground surface.
- Inexpensive method for collecting shallow soil samples.

(b) Disadvantages

- Limited depth of sampling.
- Difficult to use in hard or frozen ground.

- Difficult to use in gravelly or filled soils.

- Lack of sample retention with dry, clean sandy soils.

(c) Procedures for Use

(1) Make certain that the soil sampling tube has been decontaminated in accordance with project-specific requirements.

(2) Align the sampler in the desired orientation and advance into the soil using a constant pressure until the desired depth is achieved and/or an obstruction is encountered.

(3) Rotate the sampler 360 degrees by turning the handle and then slowly withdraw the sampler.

(4) If applicable, immediately screen the sample for volatile organic compounds using a PID after the sampler is removed from the ground. The most effective way to screen the sample is to place it in a soil sample jar, leaving one to two inches of clearance in the jar. Place the lid on the jar, shake the sample, carefully remove the lid, and test the headspace for VOCs.

(5) Compare PID readings to action levels presented in the project Health and Safety Plan. The operator of the PID must be experienced in its use and aware that factors such as temperature, humidity, and methane may affect the readings.

(6) Obtain samples (discrete or composite) and place in appropriate containers.

3.4-2.1.3 Hand Auger: Solid-stem Auger

Hand augers are effective in obtaining soil samples to depths of about five feet. The auger diameter ranges from 1.5 inches for a solid-stem auger to 8 inches for a hollow or bucket auger (see Figure 3.4-3).

Exploration with solid stem augers precludes the use of a separate soil sampling device. Soil samples are obtained either from cuttings brought to the ground surface by auger flights or directly from the auger after it has been withdrawn from the borehole. This sampling technique does not provide discrete samples.

(a) Advantages.

- o Ease of use.
- o Inexpensive method to obtain shallow soil samples.
- o Minor disturbance of ground surface.

(b) Disadvantages.

- o Does not yield a representative sample from discrete depth; sample obtained from auger flights.
- o Difficult to penetrate coarse, granular soils.
- o Rotation of auger up and down hole may result in cross-contamination of soils.
- o VOCs are not representative as volatilization may take place.

(c) Procedures for Use

The general procedure for advancing a hand auger exploration is discussed below.

(1) Decontaminate all hand auger equipment in accordance with project requirements.

(2) To make a hand auger borehole, attach the auger bit to a drill rod extension, and attach a "T" handle to the drill rod.

(3) Clear the area to be sampled of any surface debris (twigs, rocks, of litter). It may be necessary to remove the first three to six inches of surface soil for an area approximately six inches in radius around the auger location.

(4) Begin augering by pressing down on the handle while manually rotating the auger stem. Periodically remove soil

cuttings that accumulate on the ground around the auger stem. This will prevent loose material from falling back down into the borehole when removing the auger or adding drill rods. If necessary, cuttings should be screened for volatile compounds (VOCs) with a photoionization meter (PID) or for other parameters, as appropriate.

(5) Compare PID readings to action levels presented in the project Health and Safety Plan. The operator of the PID must be experienced in its use and aware of such factors as temperature, humidity, and methane on the readings provided by the PID.

(6) After reaching the desired depth, carefully remove the auger from the hole.

(7) To obtain a soil sample, remove the tip from the auger and replace it with a decontaminated sampler. (Note: When sampling directly from the auger, collect the sample after the auger is removed from the boring and proceed to Step 10).

(8) Carefully lower the sampler down the hole. Gradually force the sampler into the soil. Care should be taken to avoid smearing the borehole sides. Hammering of the drill stem to facilitate sampling should be avoided as the vibrations may cause the walls to collapse.

(9) Remove the sampler and unscrew the rods, if necessary.

(10) Place the soil sample in a decontaminated stainless steel tray and screen with a PID for VOCs. Place the soil to be analyzed into an appropriate container.

(11) Decontaminate sampling equipment after use and between sampling locations, as necessary.

3.4-2.1.4 Hand Augers: Hollow-stem Auger

Exploration using a hollow-stem auger is similar to that for a solid stem auger except that the bottom section of the auger is designed to retain a sample of soil as the auger is advanced. As a result, the borehole is advanced in intervals equal to the length of the hollow-stem auger section.

(a) Advantages

- Ease of use.
- Inexpensive method to obtain shallow soil samples.
- Minor disturbance of ground surface.

(b) <u>Disadvantages</u>

- o Difficult to penetrate coarse, granular soils.
- o Sampler section needs to be decontaminated between sample collection.
- o Potential for contaminated soils to fall from the walls of the hole as the augers are removed or reinserted into the hole.
- o Lack of sample retention in saturated sands and other loose soil materials.
- o Not good for discrete depth samples.

(c) <u>Procedures for Use</u>

See Solid Stem Auger section on procedures (3.4-2.1.3)

<u>3.4-2.1.5 Hand Augers: Bucket Auger</u>

The bucket auger is advanced in the same way as the hollow-stem auger. The bucket auger makes a larger diameter hole (e.g., 3- to 4-inch diameter) than the hollow-stem hand auger. It can be advanced to depths of 10 feet.

(a) <u>Advantages</u>

- o Ease of use.
- o Inexpensive method to obtain shallow soil samples.
- o Minor disturbance of ground surface.
- o Can be used to sample discrete depth intervals.

(b) <u>Disadvantages</u>

- o Difficult to penetrate coarse, granular soils.
- o Sampler section needs to be decontaminated between sample collection in contaminated areas.
- o Potential for contaminated soils to fall from the walls of the hole as the augers are removed or inserted in the hole.

(C) <u>Procedures for Use</u>

See Solid Stem Auger section for procedures (3.4-2.1.3)

3.4-2.1.6 Backhoes

The standard procedure for making test pits or trenches with a backhoe and the collection of soil samples from them is presented in detail in Section 3.1 Exploratory Test Pits.

3.4-2.2 Borehole Sampling

Boreholes are used when it is necessary to obtain representative soil samples at depths greater than 15 to 20 feet (beyond small to medium-sized backhoe reach) or when soil conditions or subsurface contamination suggests the use of a more discrete technique. Boreholes can be advanced using several different techniques, with casing or hollow-stem augers being the most commonly employed techniques. Section 3.2 Drilling Techniques presents a detailed discussion of the various techniques used to drill a borehole. Disturbed soil samples obtained from boreholes are most commonly collected using the following techniques and devices:

- Split-spoon and Split-tube Samplers
- Cuttings Sampling

3.4-2.2.1 Driven Split-spoon and Split-tube Samplers

The primary device for obtaining a disturbed soil sample, considered representative of the material from which it is obtained, is the split-spoon sampler. Samples obtained using this device are suitable for physical and environmental laboratory analyses. Further, when the split-spoon sampler is driven in accordance with the Annual Book of ASTM Standards, Standard Penetration Test (D 1586-84), blow count data may be used as an index of soil density or consistency.

The split-spoon sampler consists of a steel tube split longitudinally, equipped with a ball check valve in the head for venting, and a hardened steel shoe for driving, see Figure 3.4-4. When the head and shoe are removed, the split-barrel opens into two halves exposing the entire sample. The split-spoon is driven into the soil at the bottom of the borehole. The recovered sample is then described, and removed for classification and preservation. The split-spoon sampler is available with inside diameters ranging from 1.5 to 4.5 inches in 0.5-inch increments. It is also available in barrel lengths of 18 inches to 60 inches. The most commonly used split-spoons are 1.5 inches inside diameter with barrels that are 18- or 24-inches in length. The ASTM Standard Penetration Test requires the use of the 1.5-inch inside diameter spoon. Various baskets, sleeves or "trap doors" can be added to the sampler to assist in the retention of the sample during the recovery process.

(a) Advantages.

- o Readily available.
- o Easy to decontaminate.
- o Used to sample to depths exceeding 100 feet.
- o When driven in accordance with ASTM D 1586-84, the data can be used to establish geotechnical engineering parameters such as soil density or consistency.
- o Better soil recovery than hand methods.

(b) Disadvantages.

- o Lack of sample recovery in very dense or coarse gravel material.
- o Limited soil volume from discrete depth intervals.

(c) Sampling Intervals

Split-spoon samples are generally collected continuously or at every change of stratum or at 5-foot intervals. The sampling frequency should be designed to meet the required sampling objectives.

The sampling interval shall be determined on a project-by-project basis. A sufficient number of split spoons must be available at the borehole so that necessary decontamination of spoons does not excessively delay drilling. On the other hand, since obtaining the soil samples is the purpose of the exploration, drilling rates should never hurry soil logging or sample collection to the point where data quality is compromised. The drill inspector/geologist must control the situation.

(1) Continuous Sampling

Advantages

- o Allows the complete soil interval to be observed and/or screened.
- o Provides a near continuous vertical sample of the soil column sampled.
- o Can detect soil or contaminant variations that might be missed by less frequent sampling intervals.

o

Disadvantages

- o Slower rate of sampling with depth.
- o Increasing cost per sample with increasing depth.

(2) 5-foot Intervals

Advantages

- o Less expensive than continuous sampling.
- o Appropriate for relatively homogeneous soil conditions.

Disadvantages

- o May not yield enough detailed geologic information in complex deposits.
- o May miss important stratigraphic or contaminant variations.
- o Poor recovery from successive samples may yield insufficient data to characterize large vertical intervals of soil.

(d) Procedures For Use

(1) Advance the casing/augers to the required sample depth using one of the techniques described in Section 3.2 Drilling Techniques.

(2) Decontaminate all split-spoon sampling equipment in accordance with the project-specific quality assurance plan (see Section 6.1).

(3) After the borehole has been advanced to the desired sampling depth, assemble the sampler and lower it carefully to the bottom of the hole.

(4) With the split-spoon sampler set at the bottom of the hole, mark the drill rod at consecutive six-inch intervals for measuring the blows per six inches of driving. The drill rods are marked with reference to a common datum. Be certain that the bottom of the hole is at the bottom of the casing. If the sampler is not at the bottom of the casing, it should be withdrawn and the hole cleaned out again.

(5) Obtain samples by using the standard penetration test (SPT) which determines the driving resistance within the zone sampled. Drive the sampler using a 140-pound hammer with a vertical free drop of 30 inches.

Check that the vertical free drop is 30 inches by marking the drive head. The driller should use no more than two wraps of the rope around the cathead. (A cathead is a rotating horizontal drum with flanged edges. When tension is put on a rope around the cathead, the rope tightens on the drum and can be used to lift a 140 or 300 lb weight.) Be certain that the rope is fully released to permit completely free fall of the hammer. The number of blows to drive each six-inch interval should be recorded. Drive the sampler at least 18 inches, unless refusal as defined in the project specifications, is met. Samples up to 24 inches in length may be collected with appropriate sampling equipment.

(6) After driving the sampler, the drill rods may have to be turned clockwise to free them from the soil and to permit retrieval. Carefully retrieve the sampler to avoid unnecessary banging or vibration of the drill rods as these actions may cause soil to fall out of the sampler. Avoid bumping up the rods with the hammer. As an alternative to bumping the sampler free from very dense soils it is sometimes necessary to use the drill rig's hydraulic capability to pull the rods. Where washed borings are being used, the casing must be kept full of clean water at all times. This will require adding water while the rods are being withdrawn prior to sampling and when the sampler is withdrawn. The addition of water to hollow-stem augers may also be required. Where soil samples for chemical analysis are to be obtained, the water supply should be uncontaminated and verified by a sample of the field screening with a PID periodically and collecting at least one sample for chemical analyses as identified in the project work plan. (This subject is more fully discussed in Section 6.0.)

(7) When the sampler is brought to the ground surface, open it immediately, scan for VOCs using a PID, measure the length of recovery and enter significant sample data in the field book and on the boring log (see Figure 3.4-5). Loose wash at the top of the sample should not be counted as part of the recovery.

(8) Adequate recovery will be defined by the site-specific sampling plan or by the project geologist/engineer. If recovery is determined by the geologist/engineer to be insufficient, place the sampler back down the hole and advanced as follows: if the original depth is reached, drive the sampler an additional 18 inches and record the blows as a new sample; if the original depth is not reached, redrive the sampler to recover disturbed material. Record only the original blow count and note that the sample was redriven.

3.4-2.2.2 Auger-advanced Split-tube Sampler

In recent years, a split-tube sampler has been developed that fits into the bottom 5-foot section of a hollow-stem auger drill string. With this method, as the augers are advanced, the split-tube "cores" the soil for each 5-foot run. Assuming 100% recovery, this device will yield a 2½ to 3½-inch diameter by 5-foot long slightly disturbed soil sample; this is about 1-inch less than the hollow-stem auger I.D. The sampling procedure is shown on Figure 3.4-6. The procedures to be used to collect split-spoon samples by this technique follow.

(a) Advantages

- Less expensive since sampling occurs simultaneous with drilling.
- Very efficient in relatively homogeneous soil conditions.
- Can chemically screen five-foot wide samples.

(b) Disadvantages

- Sample can become disturbed during augering making geological interpretation difficult.
- May not yield detailed geological information in complex deposits.
- Poor recovery from successive samples may yield insufficient data to characterize large vertical intervals of soil.

(c) Procedures for Use

The procedure for use of the auger-advanced split-tube sampler is the same as for the driven split-spoon sampler described above in Section 3.4-2.2.1(d) except for four steps (i.e., where the sampler is placed in the borehole and advanced). Follow the steps described in the previous subsection for (1) and (2).

(3) After the augers have been advanced to the sample depth, remove the auger plug and lower the decontaminated 5-foot long split tube and lock it into the bottom 5-foot section of the auger.

(4) Place a 5-foot section of augers on the top of the drill stem and secure it to the drill head. A stroke of 5-feet is then marked on the drill head guide bars.

(5) Advance the auger at a slow, smooth rate until the 5-foot stroke is complete or an obstruction is encountered.

(6) After the advance of the auger is complete, release the drill head from the augers and retrieve the split-tube sampler from the borehole.

(7), (8), (9), (10), (11), (12), (13), and (14) follow the steps described in the previous subsection (3.4-2.2.1(d) 1 through 8).

3.4-2.2.3 Sampling Borehole Cuttings

An alternate, through less desirable method of obtaining a soil sample during drilling is from cuttings generated by wash water used to remove soil from inside a casing or from cuttings brought to the ground surface on auger flights. Samples collected in this manner are not suitable for physical or environmental analysis because of their non-representative nature. Information from cutting samples should only be used to supplement information between the intervals where representative samples are collected. Although samples collected from cuttings are not acceptable for physical or environmental analysis, a discussion of two methodologies is included for reference purposes.

(a) Wash Sampling

The term "wash boring" refers to the technique of advancing a hole by using a stream of water under pressure to remove the cuttings produced by the rotation or chopping action of the drill string. As the hole is advanced, the soil is washed to the surface where it can be caught, decanted, and saved as "wash samples" or "wet samples". Borehole cuttings of this type will give a very general picture of the subsurface conditions, but intermixing of the various strata may lead to erroneous interpretations. An estimate of the depth (or range of depth) from which the sample was obtained can be recorded on the log sheet. Much of the finer fraction will not settle out. The resulting sample will have a coarser gradation than this in-situ soil.

(b) Auger Cuttings

Auger cuttings are produced as the borehole is advanced and the auger flights transport material upward to the ground surface. Auger cuttings are reworked and the depth from which cuttings observed on the ground surface originated cannot be accurately determined. Obvious changes in auger torque or vibration may indicate changes in strata. Where geology is complex and/or critical for site characterization, this information should only be used to supplement other direct determinations of geologic characteristics.

3.4-3 STORAGE OF DISTURBED SOIL SAMPLES

When taking soil samples for environmental analyses, remove the disturbed soil samples from the sampler and place in appropriate containers. Trim the soil core after sampling so that samples can be taken from the bulk of the core rather than the surface. A single split-spoon core may provide for more than one individual sample depending on conditions encountered and lithologic changes.

3.4-3.1 Containers for Soil Samples

Representative samples to be used for physical laboratory testing and/or soil description purposes shall be placed in large mouth, round, screwed top, air-tight, clear glass jars. Typically, the size of the jars should be 8 ounces for 1-3/8-inch diameter samples and 12 ounces for 2-1/2-inch diameter samples. After environmental samples have been obtained, place the remaining specimens in air-tight jars so that the original moisture content may be preserved. The jars should be tightly capped, waxed, and suitably boxed, marked, and identified with legible labels, as directed by the geologist/engineer.

3.4-3.2 Data for Labels and Field Book

The label information should be placed on a gummed printed label that can be affixed to the jar not to the cap. Use of clear acetate tape over the label is recommended to doubly secure the label and protect the information thereon. In addition, label the jar lid with the project number, boring number, number of sample, and depths at top and bottom of the sampling interval. A labeled jar often is prepared for every sample attempted, even if there is no recovery. Place jar samples should into containers, such as cardboard boxes, with dividers to prevent movement and breakage of the jars. Label the boxes on the top and four sides to show the project number and name, the identification of the samples contained in the box, and the depth from which the samples were taken.

If all of the soil recovered is to be collected and saved, place samples into jars in six-inch increments or, where lenses or layers are clearly evident, separate the material types into different jars. Each six-inch increment or individual layer of a sample should be assigned a letter suffix, beginning with "A" at the bottom of the sample. Figure 3.4-7 shows sample selection based on individual layers while Figure 3.4-8 is based on 6-inch increments in a uniform material. If only six inches of a sample is recovered, this would be given the suffix "A". This information should also be noted on the boring log.

Sample information to be included on sample labels and in boring logs and field books should include the following information:

- o Project name and number.
- o Boring number.
- o Depths at top and bottom of sample interval.
- o Number of sample.
- o Number of blows for each six inches of penetration (blow counts).

- o Organic vapor analyzer results.
- o Date of sampling.
- o Other project-specific information (field book only).
- o Recovery in inches (field book only).

3.4-3.3 Storage and Shipment

Protect representative jar samples from the weather, including excessive heat and freezing temperatures. If the representative samples are contaminated, evidence tape or custody seals should be placed across the jar lids. For commercial shipment of contaminated samples see Section 6.3.

Initiate proper procedures for delivery to the designated laboratory when all samples have been collected. This includes packaging, shipping with sample logs, analysis request forms, and chain-of-custody forms.

Indicate the type of material on the boring log and described in accordance with the Annual Book of ASTM Standards using the Modified Burmister classification, Unified Soil Classification System (D 2487-66 and D 2488-69), or DEP approved-equivalent.

3.4-4 REPRESENTATIVE "UNDISTURBED" SOIL SAMPLES

Relatively "undisturbed" samples have traditionally been collected for the purpose of determining specific geotechnical engineering properties of soils through special laboratory tests. Relatively undisturbed samples of soil can be obtained using samplers equipped with thin-walled tubing or by block samples. Thin-wall tube samples are obtained from boreholes and, as a result, can be collected at various depths. Block samples are commonly collected from test pits or trenches and, as a result, are generally shallow, less than 20 feet. A description of appropriate procedures for each method of collection follows.

3.4-4.1 Thin-Wall Tube Samples

This collection technique consists of pressing thin, seamless tubing into cohesive soils of soft consistency for observation and laboratory testing. Although loose, fine-grained granular soils may be sampled with this method, sample retention is a problem even if the sampler device is equipped with a piston that creates a vacuum to help retain the sample in the tube. It is more easily used in non-granular, fine-grained material, such as silt or clay.

The thin-walled tubing, more commonly referred to as Shelby tubes, may be any thin-wall tubing with a tapered cutting edge. The sides of the tube are drawn in slightly to reduce sample friction against the wall of tube during penetration (See Figure 3.4-9). The tubes are usually cut in 2- to 3-foot lengths and coated with a lacquer or other rust-preventative solution. Uncoated tubes made of stainless steel or brass are also available, if desired. Tube materials and coatings compatible with project testing requirements should be selected.

Standard dimensions for thin-wall tubing are summarized in Table 3.4-1.

The thin-wall tubing may be used with a variety of sampling devices to obtain representative and relatively undisturbed samples. As with any sampling device or method, variations in design, operation, and ability to recover the sample is dependent upon the characteristics of the materials being sampled. Standard guidelines for thin-wall sampling (D 1587-83) have been established in the Annual Book of ASTM Standards, 1988. Detailed procedures are also included in the U.S. Bureau of Reclamation "Earth Manual".

Numerous thin-wall tube samplers are available, including:

- Open-drive sampler
- Piston sampler
- Stationary fixed piston sampler
- Floating piston sampler
- Retractable piston sampler
- Hydraulic (Osterberg) piston sampler
- Bishop sand sampler
- Swedish foil sampler
- Hvorslev sampler

The samplers most commonly used in Massachusetts to obtain tube samples of cohesive and/or fine-grained soils are:

- Open drive sampler
- Stationary fixed piston sampler
- Hydraulic (Osterberg) sampler

The other samplers noted are not recommended at this time because of the potential for excessive sample disturbance and/or lack of experience and familiarity in Massachusetts.

3.4-4.1.1 Open-drive Sampler

This device consists of a sampler head to which a thin-wall tube is fastened. The sample is obtained by pressing the open tube into the desired stratum at the bottom of the borehole. This sampler does not use any sample retention devices, although the sampler head is equipped with a ball check valve and vents that relieve air and water pressure buildup within the tube as it is pressed into the soil, they also prevent water pressure buildup when the sampler is pulled to the surface. (See Figure 3.4-9). Excessive penetration of the sampler under the weight of the rods may occur in very soft or loose materials, preventing accurate measurements of depth of penetration and causing disturbance of the material.

(a) Advantages

- o Simple to use.
- o Commonly available.
- o Easy to decontaminate sampler head.
- o Short amount of time required for sampling.

(b) Disadvantages

- o Disturbed and intermixed soil materials from the bottom and sides of the borehole may enter the tube as it is lowered into position, if the borehole is not cased.

- o Total or partial sample recovery is difficult without a supplemental retention system.

- o Hydrostatic pressures may disturb the sample during penetration or totally prevent the sample from entering the tube.

(c) Procedures for Use

See Procedures used to collect Thin-Wall Tube samples (3.4-4.1.4)

3.4-4.1.2 Stationary Fixed Piston (SFP) Sampler

This sampler employs the use of a sealed piston to reduce sample disturbance. Sample recovery is improved compared to the open-drive sampler (see Figure 3.4-10). The piston is prevented from moving downward by a locking cone in the head assembly. The piston can be locked and fully sealed at the bottom of the thin-wall tube so that it can be lowered into the borehole without collecting unwanted soil material.

Once the sampler is in position, the piston, through a series of small-diameter, inner actuating rods, is locked to the drill rig or the casing. Pressure is applied to the outer drill rods, forcing the thin-wall tube down from the "stationary" piston. When the full press is completed (24 inches), any pressure buildup is released through a small hole in the actuating rods. The tight seal of the piston also creates a vacuum on the sample that aids in sample retention.

(a) Advantages.

- o Reduced potential for sample disturbance.
- o Improved sample recovery.
- o Commonly available with considerable local experience in its use.

(b) Disadvantages.

- o More complex than open-drive sampler.
- o Requires more time to sample.
- o More parts to decontaminate at contaminated sites.

(c) Procedures for Use

See procedures used to collect Thin-Walled Tube samples (3.4-4.1.4)

3.4-4.1.3 Hydraulic (Osterberg) Piston Sampler

The hydraulic piston sampler is designed to obtain undisturbed samples of soft soils and soils that experience significant loss of strength as a result of disturbance. The design of the movable piston sampler varies considerably from the stationary piston sampler, the movable piston sampler consists of an inner thin-wall sampler tube and outer pressure cylinder, (See Figure 3.4-11). In the sampling position, a movable piston is attached to the top of the sampling tube and a stationary piston rests on the soil to be sampled. The sampler is activated by pumping fluids or gas through the pressure cylinder, which drives the upper piston and sampling tube down over the lower piston into the soil for a fixed distance. The piston is then withdrawn from the borehole with the sample. This frequently consists of a blade type drill bit with fluid deflectors.

(a) Advantages.

- o Easier to use than the stationary fixed piston (SFP) sampler.
- o Improved sample recovery.
- o Available, with considerable local experience.
- o Less time required than the SFP to obtain a sample.

(b) Disadvantages.

- o More time to decontaminate than for other samplers.

(c) Procedures for Use

See procedures to collect Thin-Walled Tube samples (3.4-4.1.4)

3.4-4.1.4 Procedures Used to Collect Thin-wall Tube Samples

The following steps are applicable to all thin-wall tube sampling:

(1) Advance the casing/augers to the required sample depth using the procedures described in Section 3.2, Drilling Techniques.

(2) Decontaminate all sampling equipment in accordance with the project-specific quality assurance plan.

(3) After the borehole has been advanced to the required sample depth, lower a "clean-out" auger into the borehole to remove loose, disturbed soils present at the bottom of the borehole.

(4) Assemble the thin-wall tube sampler and lower to the bottom of the borehole. The depth to the bottom of the borehole must be carefully measured to ensure the sampler is not "resting" on the soils at the bottom of the hole.

(5) Advance the sampler as noted below:

Open-Drive Sampler. Advance the sampler by pushing the drill rods downward in a continuous steady motion at a rate of about 0.5 feet to 1.0 foot per second.

Fixed Piston Sampler. Lock off the actuating rods so the piston will remain fixed on the soil surface. Advance the sampler by pushing downward on the drill rods at a rate of about 0.5 feet to 1 foot per second.

Hydraulic (Osterberg) Piston Sampler. Secure the drill rods at the ground surface so that the bottom piston is at the soil interface. Advance the sampler by pumping clean water down the drill rods. Continue pumping water until return of water is observed coming up the inside of the casing.

(6) Once the advance of the sampler is complete, wait 10 minutes or more before sample withdrawal.

(7) Rotate the drill rods by hand two revolutions clockwise to shear off the end of the sample.

(8) Remove the sampler from the borehole with extreme care to minimize sample disturbance.

(9) Scan the sampler with a PID to determine whether detectable levels of VOCs are present. Carefully remove the sampler head from the sample tube and remove soft disturbed material from the top of the sample. The sample tube must be kept in an upright vertical orientation at all times. Measure the length of sample recovered and record on the boring log.

(10) Remove about 1/2-inch of undisturbed soil from each end to allow room for the placement of seals. The soil cleaned from each end of the tube can be used for visual classification of the sample and head space analysis.

(11) The space at each end of the tube is sealed using flexible microcrystalline wax such as Socony Vacuum Product 2300 or equivalent, or with expandable packers. Paraffin is not acceptable. Fill empty portions of the tube filled with clean inert sand.

(12) Close the ends of the tube with tight-fitting metal or plastic caps, and wrap the seam between the cap and tube with tape. Finally, dip the ends repeatedly in hot wax, completely covering the tape, to ensure a good seal.

(13) Label the sample container and the top cap by writing on them with an indelible marker or by affixing a label. Locate all labeling on the top one foot of the tube. Include the following information on the tube: the project number, project name, date of sampling, boring number, sample number, zone of sampling, and any other information the field engineer/geologist feels is pertinent. Detailed information must also be permanently recorded in a field log. In addition, the tube shall be marked TOP and BOTTOM so that the orientation of the soil sample is known.

(14) Vertically place the tube samples in a container designed to relieve shock, vibration, and disturbance during storage and shipment.

3.4-4.2 Rotary Core Soil Samples

A variety of core barrels that were originally developed for drilling and sampling bedrock have been modified or adapted to obtain "undisturbed" overburden samples in very dense or partially cemented soils. These core barrels are used when the more conventional thin-wall samplers cannot penetrate the selected geological unit.

There are many variations in the type and mechanics of these core barrels, which are commercially available under a variety of trade names.

Single-wall or single-tube core barrels equipped with saw-tooth cutter bits have been used to a limited extent in sampling soils. However, the samples are usually disturbed by intermixing, swelling, or contamination with drilling fluid. Core barrels equipped with non-rotating inner liners are more suitable for overburden sampling.

Two of the more commonly used samplers for traditional geotechnical engineering studies are the Denison and Pitcher samplers. However, because of the potential for introduction of drilling fluids into the sample as the sampler is advanced, their use is not recommended for collection of environmental samples. A contractor proposing the collection of environmental samples using either of these devices should submit a detailed protocol for sample collection to DEP for review and approval. A brief description of each sampler and its sampling technique is presented below.

3.4-4.2.1 Denison Sampler

The Denison sampler is designed to recover relatively undisturbed thin-wall samples in dense sand/gravel soils, hard clays, partially cemented soils, or soft and weathered rock. The sampler consists of a double-tube, swivel-type core barrel with a non-rotating inner thin-wall steel or brass liner designed to retain the sample during penetration and subsequent transportation to the laboratory (see Figure 3.4-12).

The inner liner tube of the Denison sampler has a sharp cutting edge, which can be varied to extend from zero to about three inches beyond the outer rotating cutter bit. The amount of extension can be varied by means of interchangeable saw-tooth cutter bits that are preselected depending on the anticipated formation to be sampled. The maximum extension is used in relatively soft or loose soils and a cutting edge flush with the coring bit is used in hard or cemented formations. This sampler is generally effective in homogeneous soils. An important feature of the Denison sampler is a system of check valves and release vents which relieve the hydrostatic pressure buildup within the inner sampling tube, improving sample recovery, and minimizing pressure disturbance of the sample.

The Denison sampler is rotated into a formation in the same manner as conventional rock coring procedures. It is designed for use with water, mud, or air and is available in five sizes, ranging from 2.94 inches to 7.75 inches O.D. A schematic drawing of the Acker-type Denison rotary core barrel sampler is shown on Figure 3.4-12.

The Denison sampler is not a practical tool for sampling loose sands or soft clays, as the sample retention devices are usually inadequate for these materials. The presence of cobbles and boulders also will present major difficulties for penetration and recovery. The saw-tooth bit, with which the Denison is usually equipped, is not capable of coring hard boulders, which may cause collapse of the inner sampling tube if it is in an extended position.

3.4-4.2.2 Pitcher Sampler

The Pitcher sampler also was developed to recover relatively undisturbed thin-wall samples in formations that are too dense for conventional thin-wall sampler penetration. The Pitcher sampler consists of a single-tube, swivel-type core barrel with a self-adjusting, spring-loaded inner thin-wall sample tube which telescopes in and out of the cutter bit as the hardness of the material varies, see Figure 3.4-13. This telescoping aspect eliminates the need to pre-select a fixed inner barrel shoe length as is necessary with the Denison sampler.

The inner steel or brass thin-wall liner tube has a sharp cutting edge which projects a maximum of 0.5 feet beyond the saw-tooth cutter bit in its normal assembled position. As the sampler enters the borehole, a sliding valve directs the drilling fluid through the thin-wall sample tube for a thorough pre-flushing of the borehole. When the sample tube comes in contact with the bottom of the borehole, it telescopes into the cutter barrel and closes the sliding valve, which diverts the drilling fluid to an annular space between the sample tube and the cutter barrel. This sliding valve arrangement allows the circulation of drilling fluid to remove the borehole cuttings during sampling and prevents disturbance of the recovered sample by the drilling fluid.

The spring-loaded inner sample tube automatically adjusts to the density of the formation being penetrated. In very soft materials, it will extend as much as 0.5 feet beyond the cutter bit; as the formation density increases, the sample tube telescopes into the outer core barrel and compresses the control spring, which in turn exerts a greater force on the tube to insure adequate penetration. In extremely dense formations or obstructions, the sample tube will retract completely into the outer core barrel to allow the cutter bit to penetrate the obstruction. The Pitcher sampler is rotated into the unconsolidated formation in the same manner as conventional rock coring techniques. The sampler is designed for use with either water or mud and has been available in four sizes, ranging from 3.0 inches to 5.0 inches O.D. Reportedly, only the 5.0-inch O.D. sampler, which utilizes 3-inch O.D. thin wall sampling tube is presently on the market.

In highly variable formations, a major advantage of the Pitcher sampler is its telescoping sample tube, which prevents collapse of the sample tube and prevents fluid erosion of softer layers. However, the Pitcher sampler, like the Denison, is not capable of coring very large and intact cobbles and boulders.

3.4-4.3 Block Samples

One of the oldest, and considered by many as the most reliable, methods of obtaining undisturbed samples for laboratory testing consists of cutting large blocks of soil from natural, in-situ formations. Block samples should be obtained in accordance with procedure described in the Annual Book of ASTM Standards Volume 4.08, Soil and Rock (ASTM 1988).

3.4-5 PROBLEMS AND SUGGESTED SOLUTIONS

Particular advantages and disadvantages of the various subsurface sampling techniques and equipment have been discussed within the preceding sections. However, limitations and difficulties may be encountered during the exploration program that are common to all soil sampling techniques. These are usually the result of site-specific geological conditions and not necessarily a function of the equipment or procedure.

3.4-5.1 Inadequate Sample Recovery

Inadequate sample recovery can be influenced by such factors as:

- Residual cuttings in the casing prior to driving the sampler.
- Loss of sample.
- Blockage of sampler.
- Densification or frictional resistance.

3.4-5.1.1 Residual Cuttings

As borings are advanced, cuttings must be removed. In cased borings, the cuttings are removed using water that is forced down and out of the drill rods, carrying the cuttings to the top of the casing. The time required to flush the cuttings from the casing increases as the hole becomes deeper. The water velocity necessary to flush the cuttings increases as the size and weight of the individual soil grains increases. As a result, it may become difficult if not impractical to flush the casing "clean" as the depth of the borehole increases. The ability to flush the casing can be improved by using a more powerful pump, reducing the size of the annulus between the casing and drill rods, and, with the prior approval of DEP, through the use of additives mixed with the drill water to increase the viscosity of the drilling fluid.

In hollow-stem augers, cuttings are kept from the interior of the augers by the "plug" (pilot bit) at the bottom of the augers. However, when the augers are below the water table, soils are most likely to "flow" up into the augers after the plug is withdrawn. This is caused by the unequal hydrostatic pressure that exists between the soil at the base of the augers and the fluid level in the augers. Flow of soil into the bottom of the augers can be limited by keeping the water level in the augers/casing above the water table. If the soil at the base of the augers/casing is under hydrostatic pressures in excess of the water table, it may be necessary to use drilling additives to increase the density of the fluid to prevent artesian flow into the augers/casing. This solution is subject to prior approval by DEP at publicly funded sites. At other sites, the consultants report on field activities should explicitly describe the use of drilling additives.

3.4-5.1.2 Loss of Sample

Various sampling devices are equipped with check valves, pressure release valves, sample retaining springs, baskets, or lifters. These devices are designed to help retain soil samples. These devices should be checked frequently; they must be kept in good working order. In addition to the sample retention devices, sample recovery of soils
sensitive to disturbance can be improved by using extreme care not to vibrate or hit the drill rods as the sampler is withdrawn from the borehole.

3.4-5.1.3 Blockage of Sampler

Poor recovery may be the result of the presence of material large enough to block the entry of soil into the sampler. As a result, the sampler is either advanced pushing the obstruction ahead with no soil recovery, or does not advance due to resistance by the soil beneath the obstruction. The obstruction can be penetrated by:

- o Advancing the augers/casing through or past the obstruction.

- o Drilling ahead of the casing in an effort to crush or "push aside" the obstruction.

- o Coring the obstruction.

3.4-5.1.4 Densification or Frictional Resistance

Relatively loose or soft soils may decrease in volume during sampler penetration. Such soils may develop sufficient frictional resistance to prevent entry into the sampler before the sampler is completely advanced.

3.4-5.2 Sample Disturbance

A problem common to all forms of soil sampling is sample disturbance, influenced by:

- o The type of soil to be sampled.
- o Sampling equipment.
- o Diameter of the sampling equipment.
- o Method of advancing the sampler.
- o Drilling methodology.
- o Borehole disturbance.

Selection of the appropriate drilling and sampling methodology must be consistent with the objectives of the investigative effort. Disturbance of soil samples obtained for environmental site assessments is not a major concern for most projects. The most important aspect of an environmental sample is that it be representative of the material from which it is obtained. Disturbance of samples is a significant factor when the samples are to be used in laboratory tests to determine specific engineering parameters.

The American Society for Testing and Materials (ASTM) publication Special Technical Publication (STP) 483, "Sampling of Soil and Rock" (1970) presents several technical papers by various authors regarding sampling methodologies and associated sample disturbance.

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SECTION 3.4
IN-SITU SAMPLING OF SOIL

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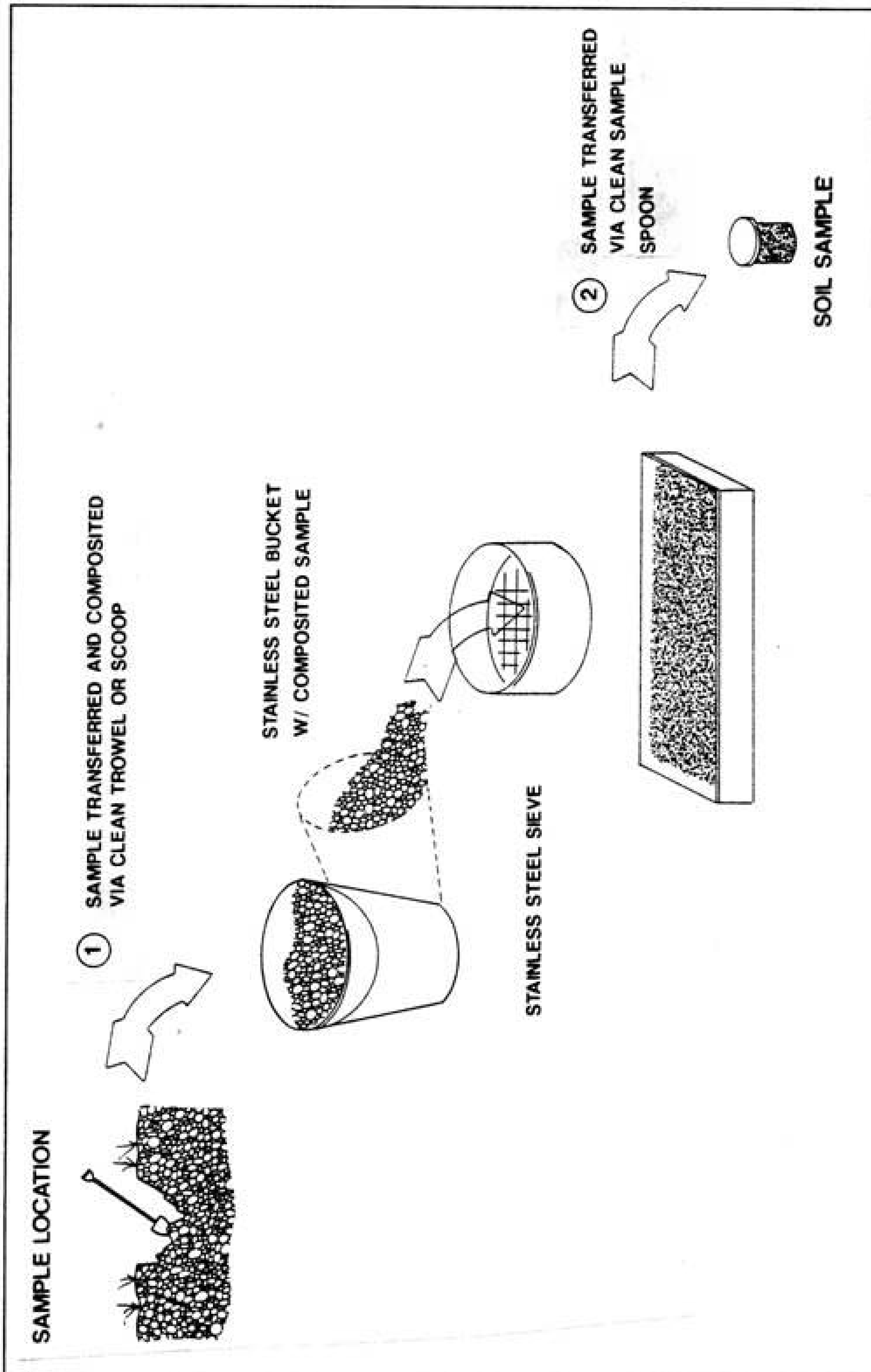
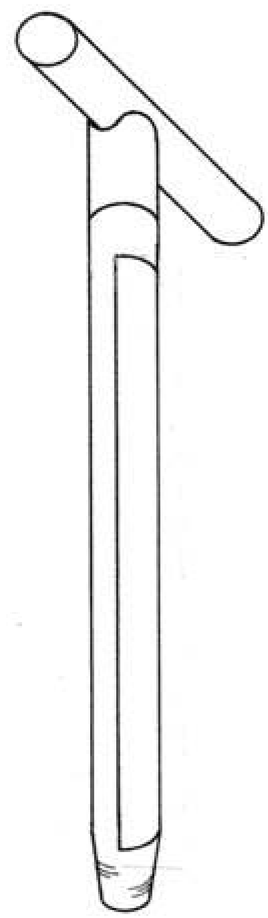


Figure 3.4-1
Schematic of Surface Soil Sampling.

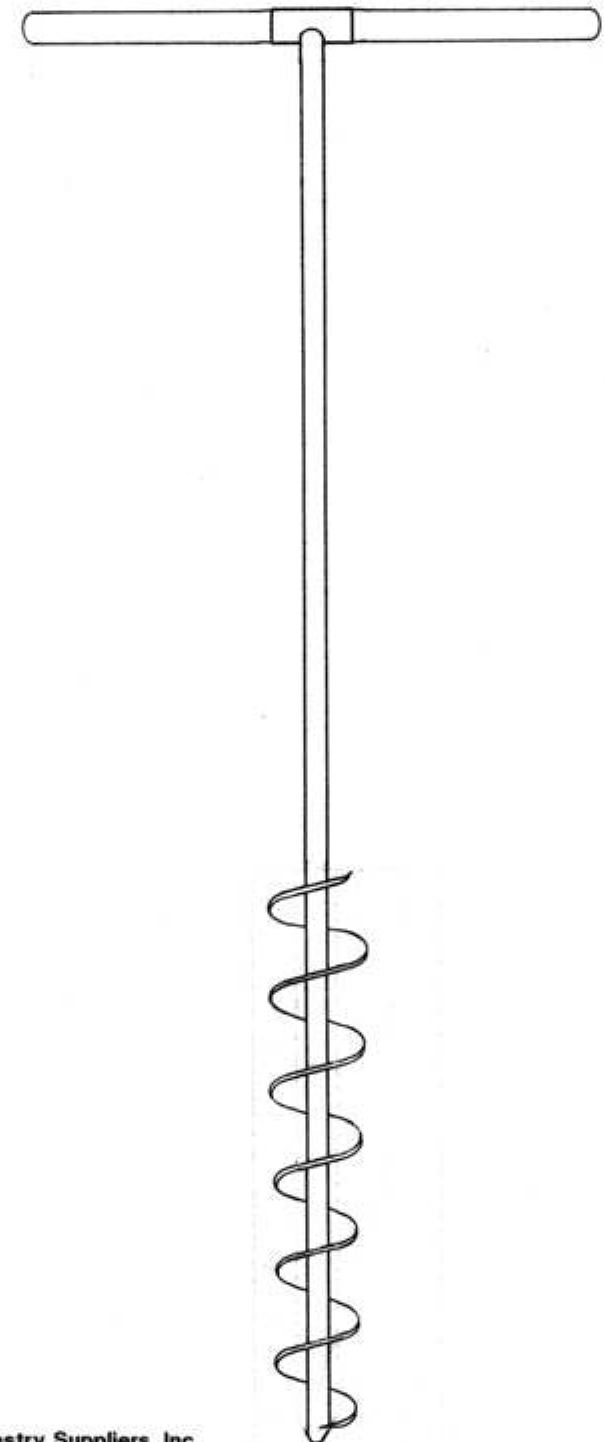
Source: MADEP



Source: After JMC Soil Investigation Equipment Catalogue No. 8

Figure 3.4-2

Soil Sampling Tube.



Source: After Forestry Suppliers, Inc.
Catalogue No. 36

Figure 3.4-3

Hand Auger.

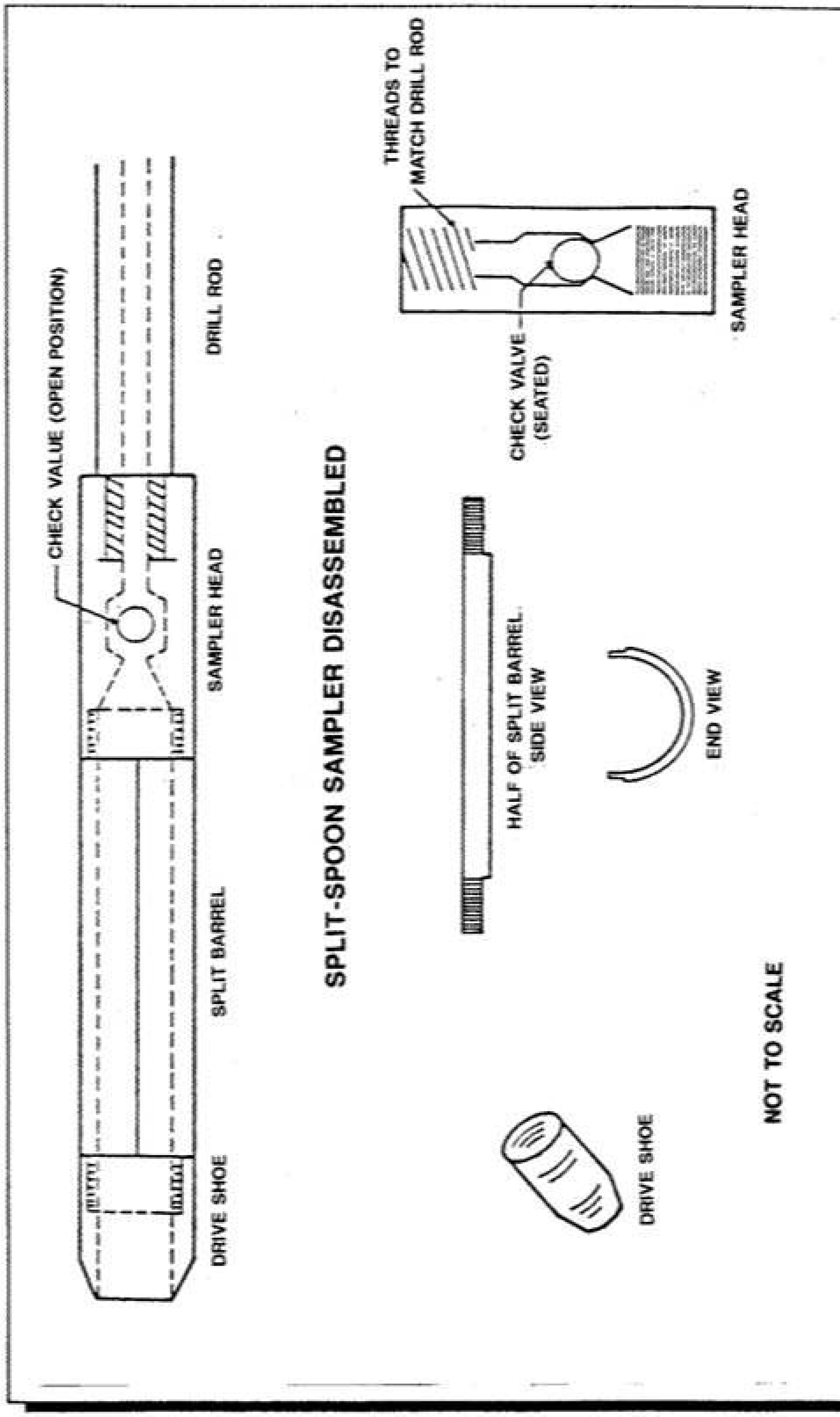
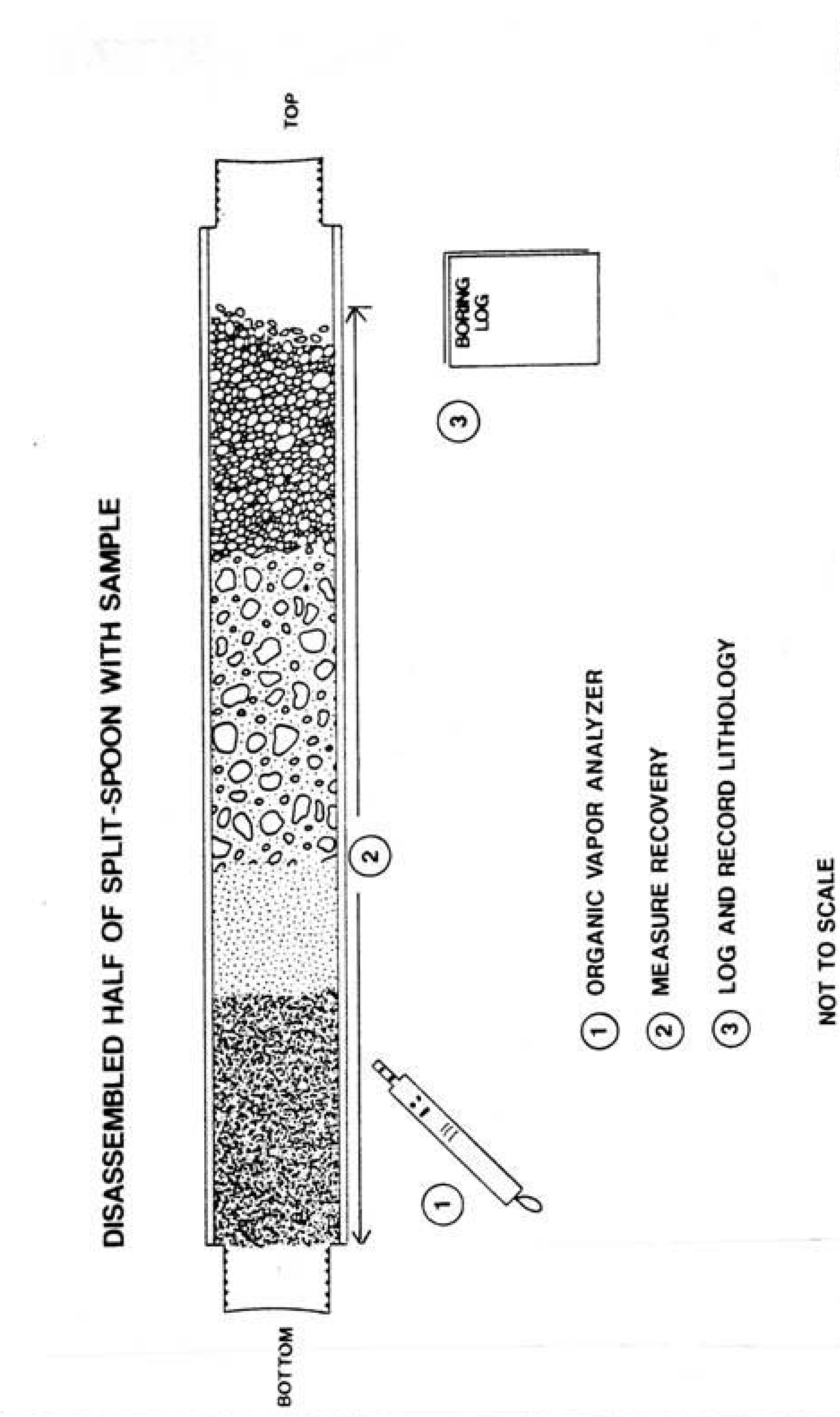


Figure 3.4-4
Split-spoon Sampler.

Source: Modified after CME Catalogue



Source: Modified after CME Catalogue

Figure 3.4-5

Schematic of Split-spoon Soil Sample Logging.

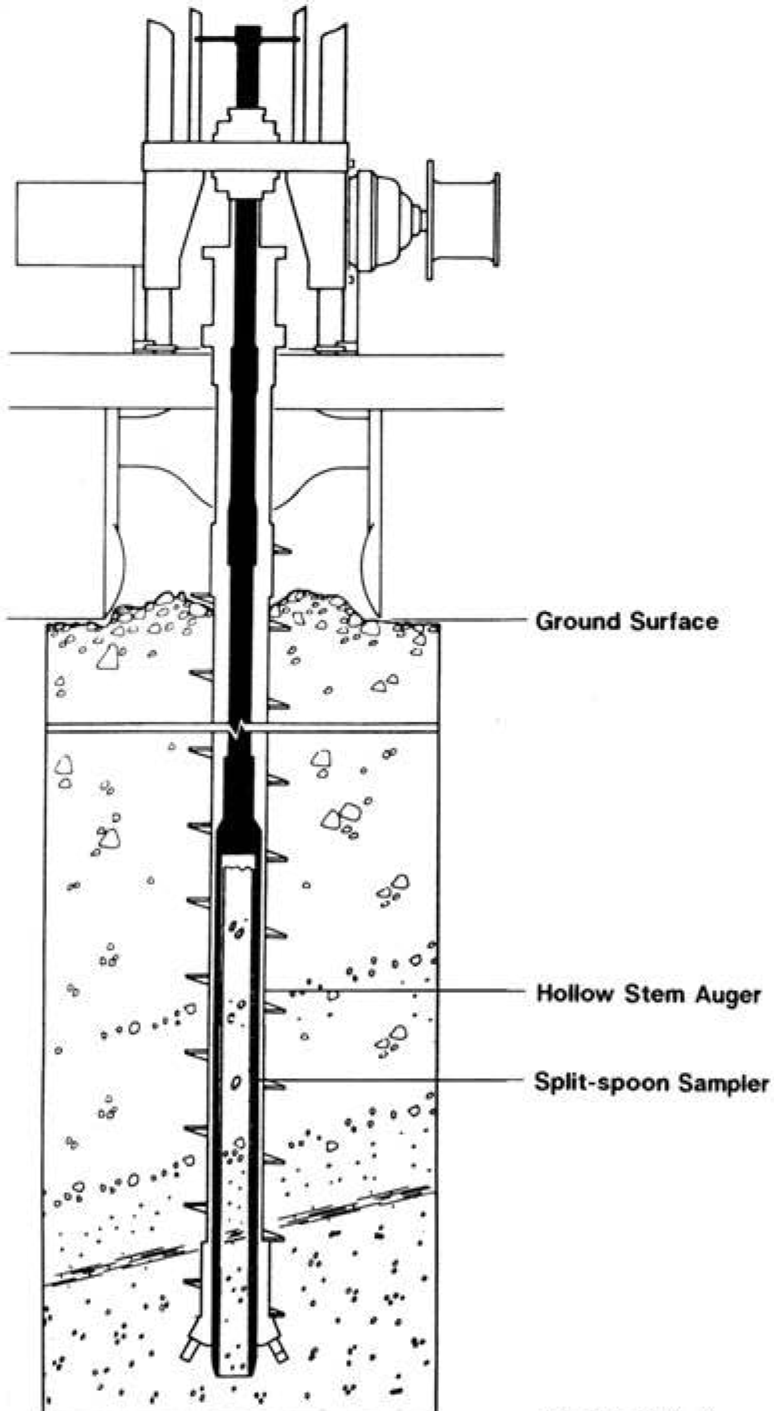
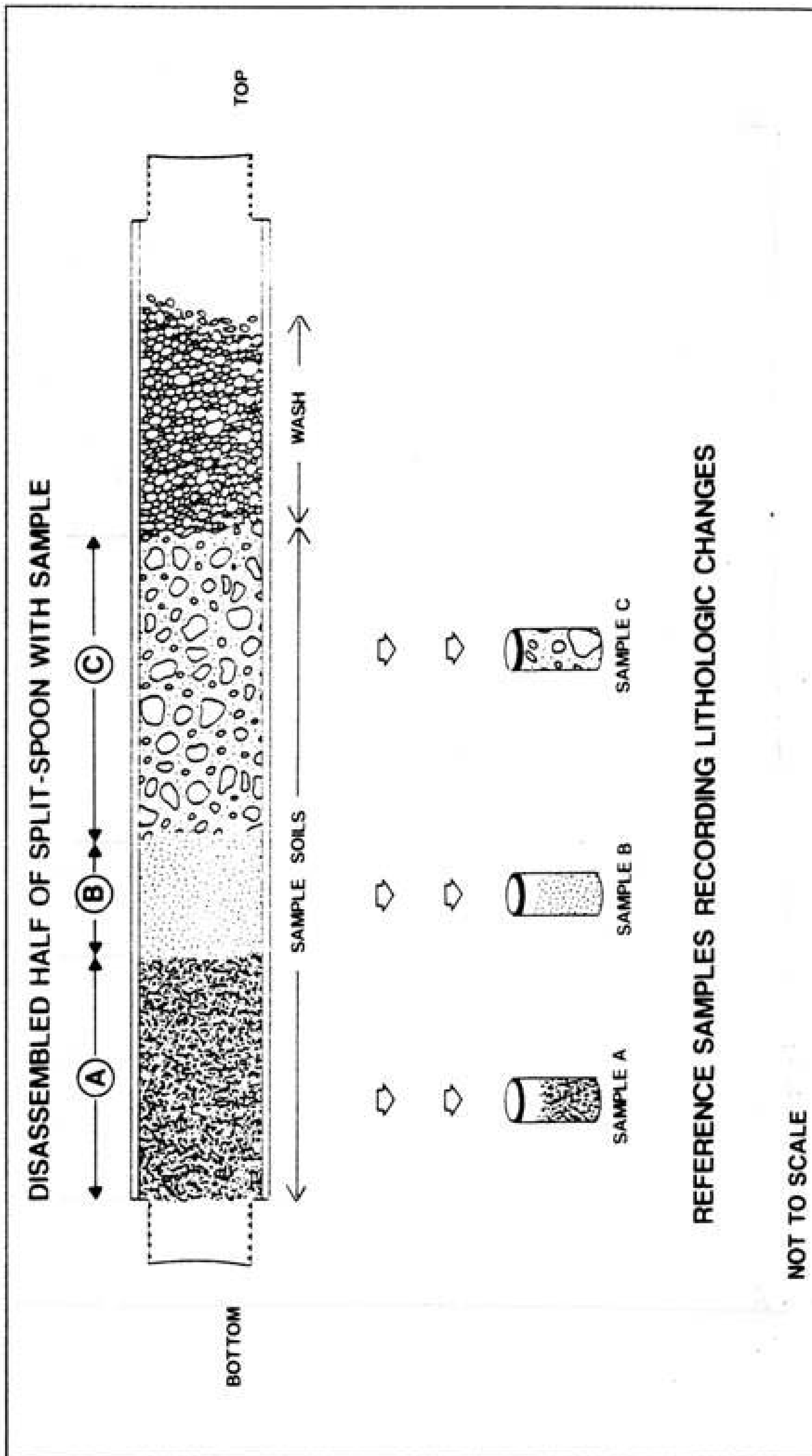


Figure 3.4-6

Source: CME Brochure

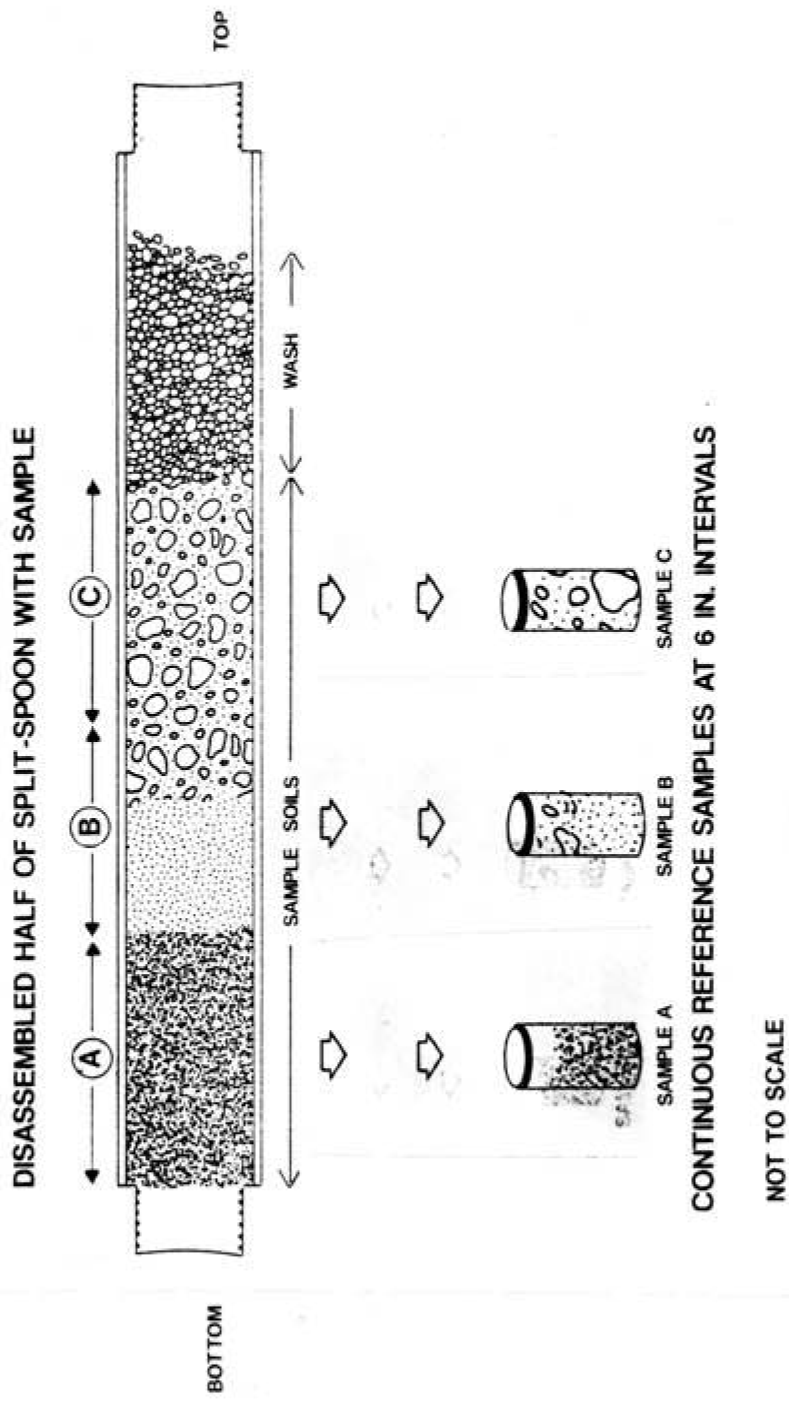
Auger-advanced Split-spoon Sampler.



Source: Modified after CME Catalogue

Figure 3.4-7

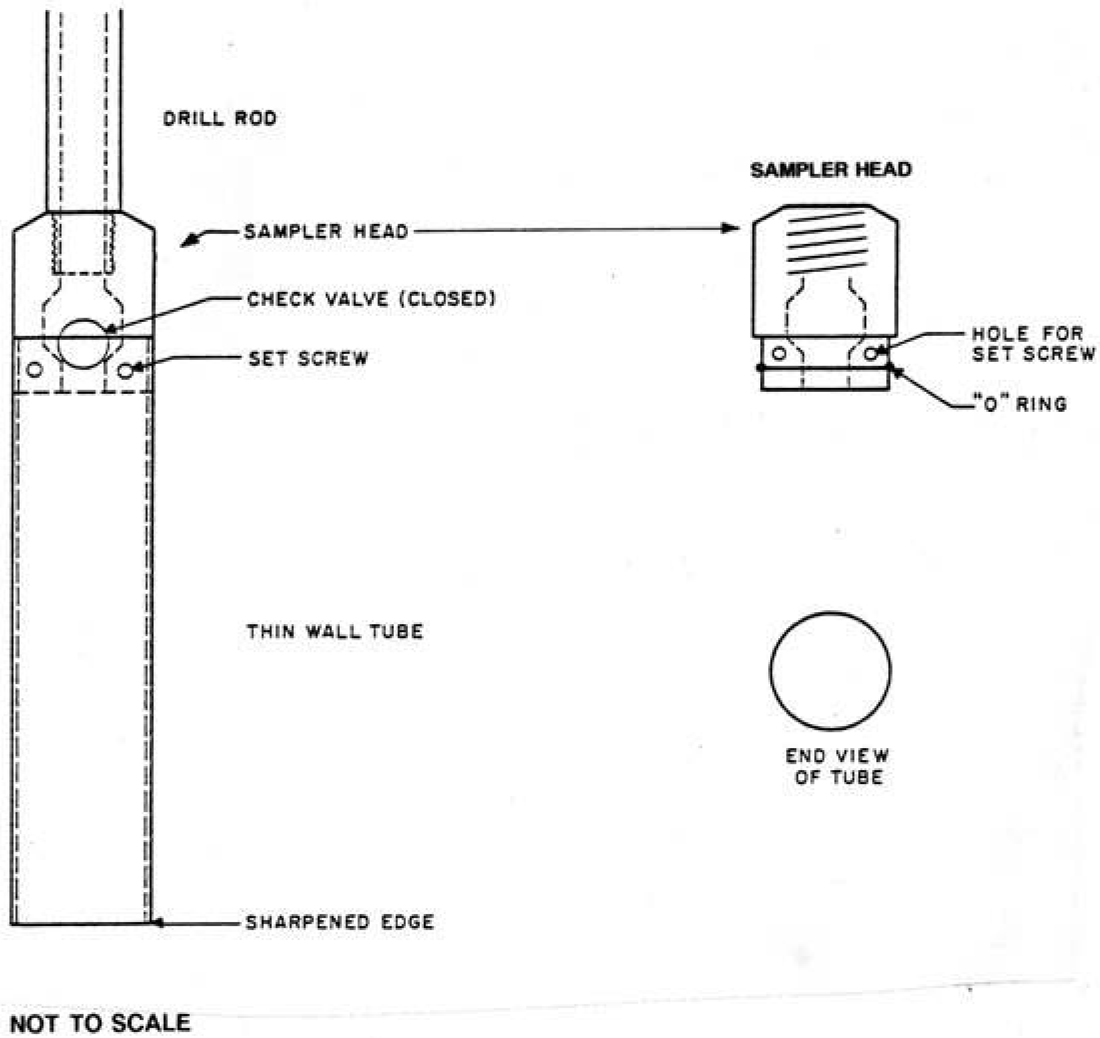
Split-spoon Samples Recording Lithologic Changes.



Source Modified after CME Catalogue

Figure 3.4-8

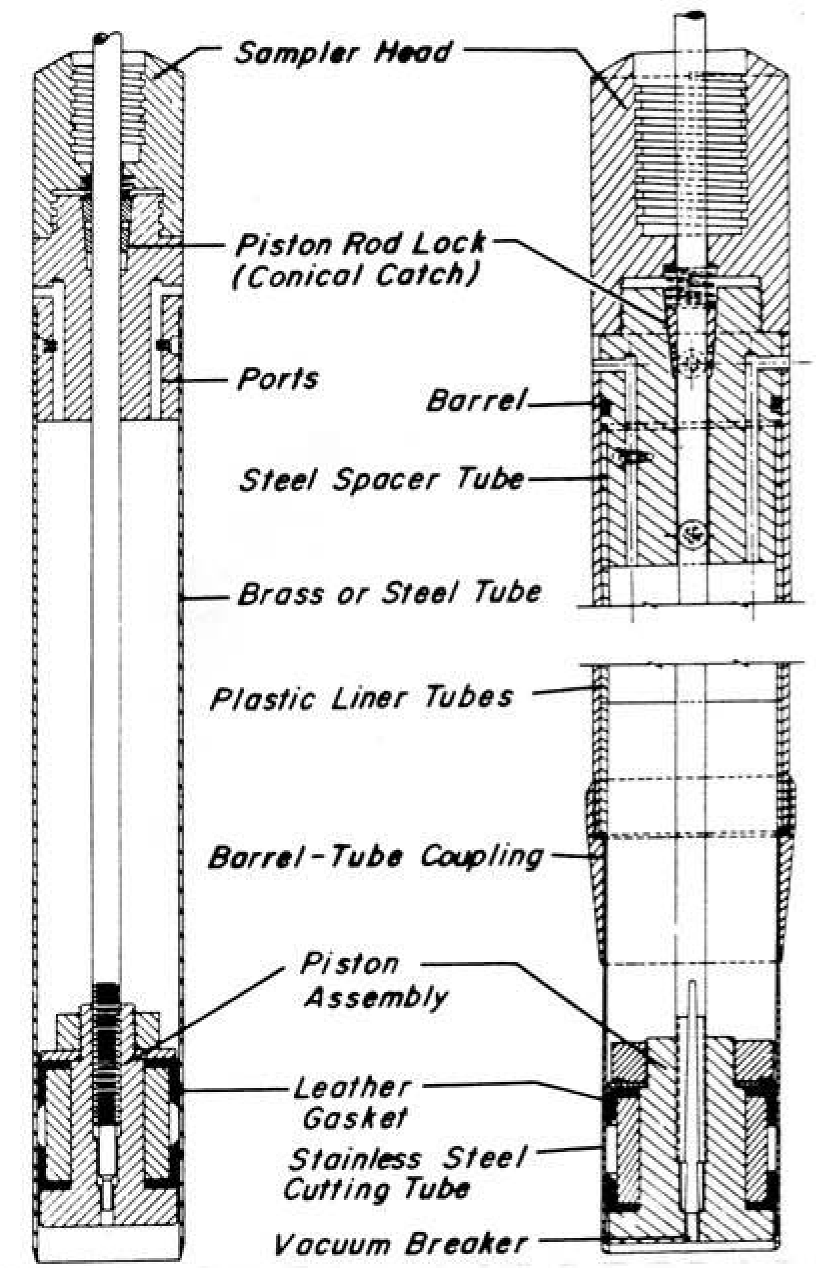
Split-spoon Samples at 6-inch Intervals.



Source Modified after Winterkorn et al. (1975)

Figure 3.4-9

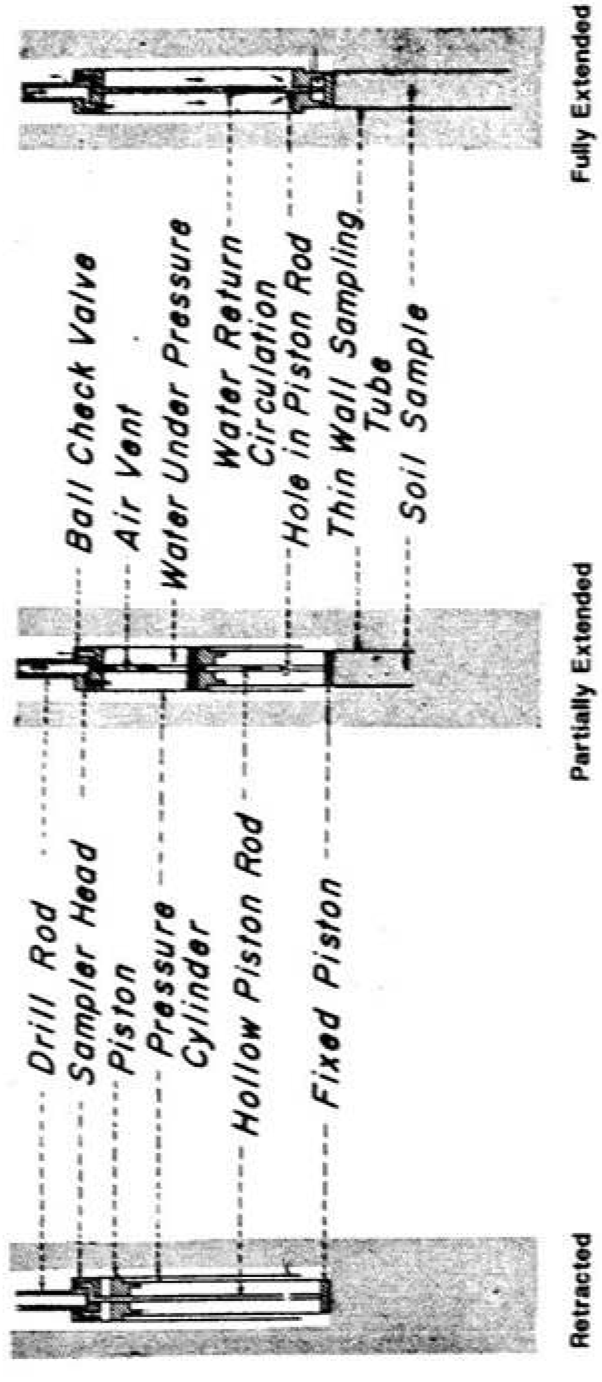
Thin Wall Sampling Tube.



Source: Winterkorn et al. (1975)

Figure 3.4-10

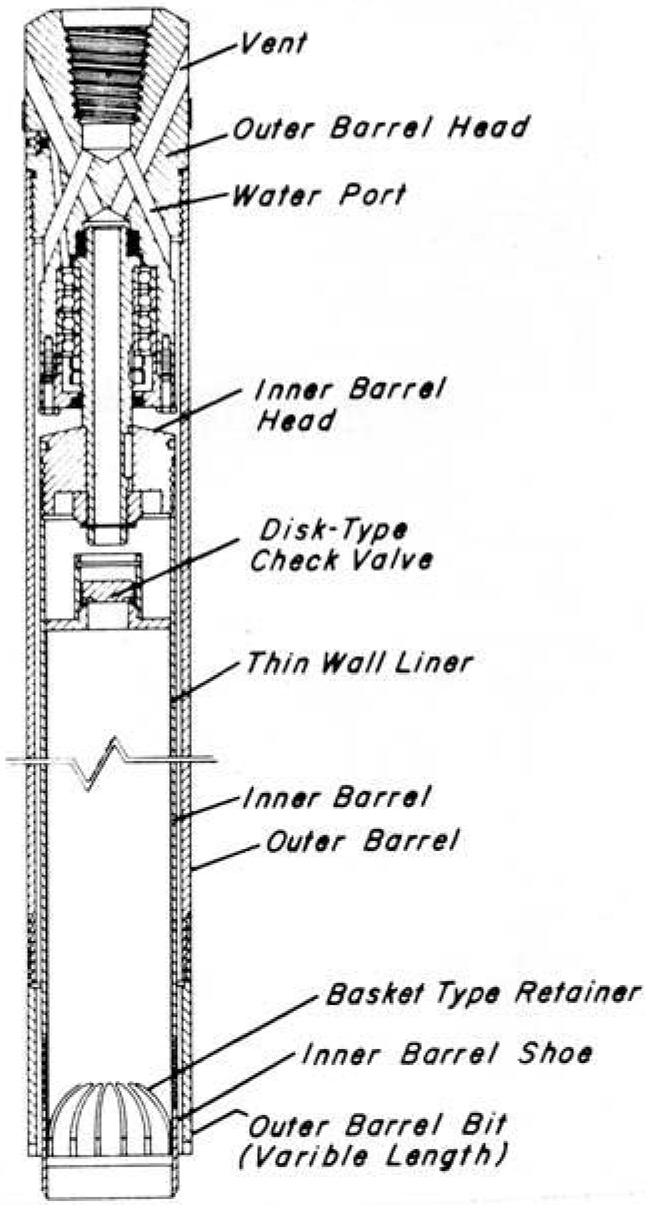
Stationary Fixed Piston Sampler.



Source: Winterkorn et al. (1975)

Figure 3.4-11

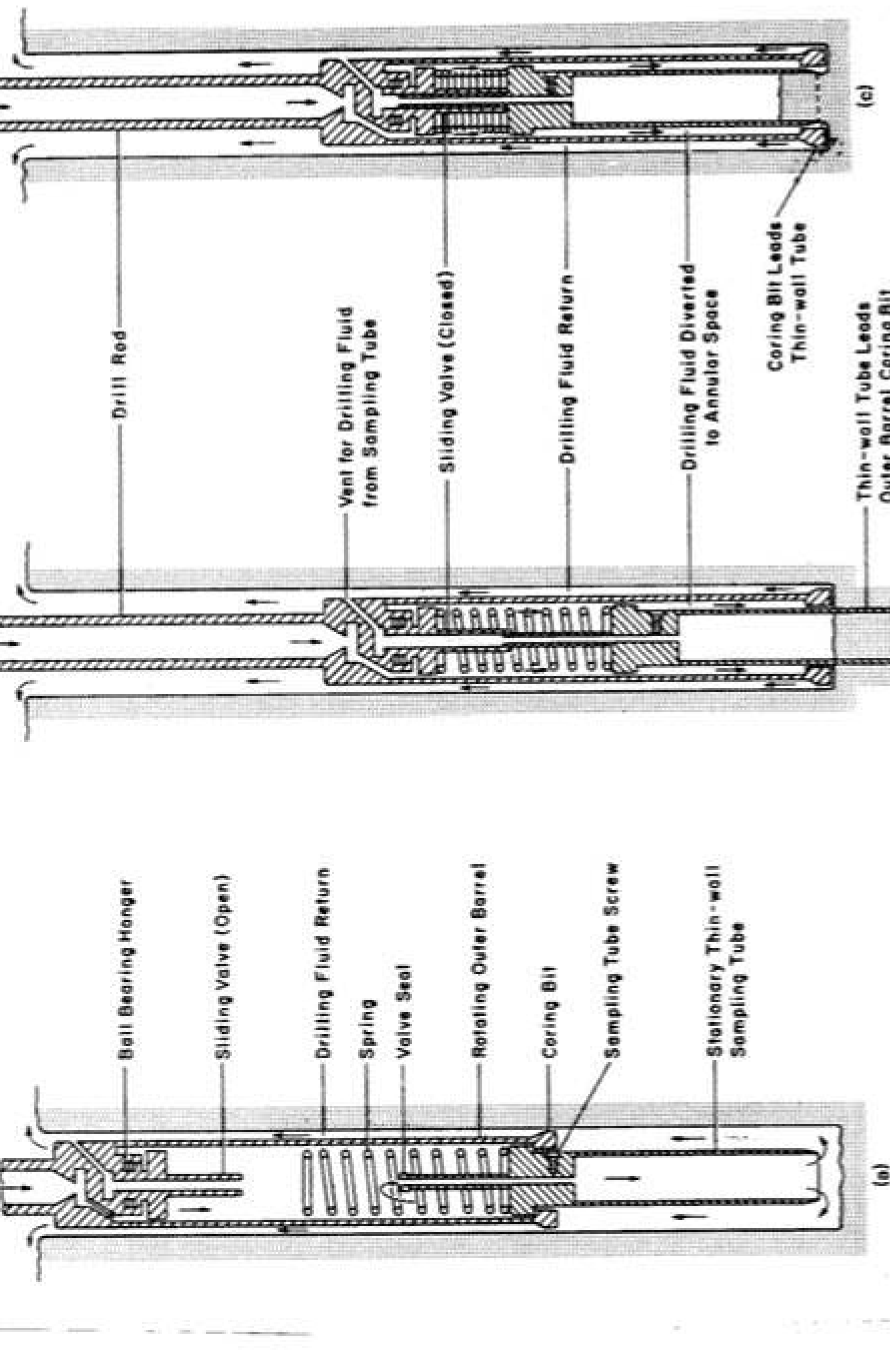
Hydraulic (Osterberg) Piston Sampler Operation.



Source: Winterkorn et al. (1975)

Figure 3.4-12

Denison Sampler.



Source: Winterkorn et al. (1975)

Figure 3.4-13

Pitcher Sampler.

Dimensions			
I.D.		O.D.	
in.	mm	in.	mm
1.878	48	2.000	51
2.838	72	3.000	76
4.170	106	5.000	127

Source: After Winterkorn et al. (1975)

Table 3.4-1

Standard Dimensions for Thin-wall tubing.

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SECTION 3.5 SOIL CLASSIFICATION

SECTION 3.5
SOIL CLASSIFICATION

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SECTION 3.5 SOIL CLASSIFICATION

3.5-1 PURPOSE

The purpose of soil classification is to systematically group soils with similar physical characteristics in the same classification category. The use of a soil classification system produces a consistent description of soil samples that can be readily understood by engineers, geologists, drillers, and other members of the project team. Soil classification systems group soils based on physical characteristics (e.g., grain size, gradation, and plasticity). General engineering and hydrologic properties of soils can be estimated from these physical characteristics allowing rapid preliminary assessment of site conditions during a field investigation program. Often this preliminary assessment of the subsurface soil conditions is the primary basis for modification of a field investigation program when little time is available for laboratory analyses.

A systematic grouping of similar soil types based on physical characteristics aids in the identification and correlation of subsurface stratigraphy. Accurate identification of subsurface variations is an essential element in contamination investigations because the existence of subsurface structures or heterogeneities can have a significant impact on rates and directions of contaminant movement.

Care should be taken to assure that soil-classified samples are representative of the strata from which they were obtained. If significant subsurface variation occurs or if poor recovery is obtained, it should be noted on the boring log. Soil samples may be obtained from surface sampling programs, borings, and test pits. Samples should be collected and labeled according to the procedures described in the Standard Reference (SR) for that specific sampling method (see Section 3.4).

Soils are classified on the basis of visual-manual tests and laboratory tests. This SR describes visual-manual classification techniques that are used in the field; some applicable standard laboratory testing techniques are discussed in Section 3.8 Laboratory Testing of Soil and Rock. With adequate training and experience, it is possible to accurately and consistently classify soils on the basis of visual-manual field tests. The comparison of visual-manual classifications to laboratory test results (e.g., grain-size analyses) is necessary to confirm and refine the field descriptions.

3.5-2 CLASSIFICATION SYSTEMS

Several soil classification systems have been developed to describe soils, including the Unified Soil Classification System; the Burmister System; and systems developed by the U.S. Department of Agriculture (USDA), American Association of State Highway Officials (AASHO), Massachusetts Institute of Technology, and British Standards Institute. Table 3.5-1 is a comparison of the components of various soil classification schemes as they relate to grain size.

The Unified Soil Classification System is the most commonly used classification system in the U.S. Developed by A. Casagrande in 1953, it has been adopted by the U.S. Bureau of Reclamation and several other state and federal agencies. Another classification system commonly used in the northeastern U.S. is the

Burmister System, developed in the 1940s by the American Society of Engineering Education.
As shown in Figure 3.5-1, the major difference between the Unified System and Burmister System is in the breakdown of the coarse-grained components. Additionally, the Burmister System includes a determination of the percentage by weight of various soil components, and a description of the relative percentages through the use of the following modifiers: and, some, little, and trace. A combination of the Unified System and the Burmister System has been used as the procedure for classifying soils described herein. A list of key soil properties, along with specific field tests, is described in the following section.

3.5-3 METHODOLOGY

For the purpose of providing consistent sample descriptions, the flow chart (Figure 3.5-2) can be used as a general guide for the soil classification process. The following soil characteristics/properties have been identified in the sample description in the order of presentation:

- Color (Section 3.5-3.1)
- Gradation: coarse-grained soils versus fine-grained soils (Section 3.5-3.2)
  - -coarse-grained soil identification procedures (Section 3.5-3.2.1)
  - -fine-grained soil identification procedures (Section 3.5-3.2.2)
- Gradation Designation (Section 3.5-3.3)
- Relative Density/Consistency (Section 3.5-3.4)
- Particle Angularity (Section 3.5-3.5)
- Moisture Content (Section 3.5-3.6)
- Structure (Section 3.5-3.7)
- Reaction to Hydrochloric Acid (Section 3.5-3.8)
- Geologic Name (Section 3.5-3.9)
- Unified Classification Designation (Section 3.5-3.10)
- Special Conditions or Notes (Section 3.5-3.11)

3.5-3.1 Color

Sample color should be determined, if possible, immediately after the sample is retrieved, while it is still at its natural moisture content. Soil color is particularly important in the description of fill, organic, weathered, or natural soils that may have been contaminated. Sample layers or patches of different coloration should be noted.

Color descriptions may vary considerably from one person to another; the use of a Munsell Soil Color Chart will assure more consistent color descriptions. The Munsell Soil Color Chart uses standard color chips against a neutral background. Small holes in the color chart next to the chips allow the user to view the sample next to the chip to find an accurate match. Although not typically used in soil classification, a color can be described by a series of symbols representing the hue, value, and chroma (example: 5YR 6/4).

3.5-3.2 Gradation: Coarse-grained Soils Versus Fine-grained Soils

Individual soil particles are given the following descriptors based on size: boulders, cobbles, gravel, sand, silt, and clay. Table 3.5-1 presents the particle size descriptors by their size in inches or standard sieve size, and familiar reference sizes for approximation purposes.

For the purpose of sample classification, soils will be broken down into two major groups according to weight percentages: coarse-grained soils and fine-grained soils.

- Coarse-grained soils are defined as containing more than 50 percent by weight larger than the No. 200 sieve (sands and gravels, up to 3 inches in diameter). Section 3.5-3.2.1 presents procedures for classifying coarse-grained soils according to the Burmister System.

- Fine-grained soils are defined as containing more than 50 percent passing the No. 200 sieve (silts and clays). Section 3.5-3.2.2 presents procedures for classifying fine-grained soils according to the plasticity and the percentage of clay versus silt as estimated from various field tests.

3.5-3.2.1 Coarse-grained Soil Identification Procedures

The Burmister System provides a consistent framework to estimate the distribution of gravel-, sand-, and silt-size particles. Percentage ranges in weight for various particle sizes are given in Table 3.5-2.

Two examples of a sample description using Burmister System designations are as follows:

Fine to Medium SAND, little coarse gravel, trace to little silt.

Fine SAND and silt, trace medium to coarse sand, and fine gravel.

When a sample contains significant amounts of silt- and clay-size particles (greater than 12 percent by weight), the fine portion will be classified by procedures for fine-grained soils in Section 3.5-3.2.2. The presence of boulders and cobbles will be indicated and, if possible, the percentage estimated if observed in test pits or excavations.

3.5-3.2.2 Fine-grained Soil Identification Procedures

Field procedures for the determination of fine-grained soil properties are described in this subsection. After performance of one or more of the field tests, the fine-grained soils are given a material designation (e.g., silty clay or clayey silt) and a plasticity description (e.g., slight, medium, or high). Appropriate designations (ASTM 1988) relating to the field test classifications are given in each section. The following field tests may be applied to differentiate between cohesionless silt and plastic silty clay soils.

(a) Dilatancy

A pat of wet soil is shaken in the palm of the hand and alternately squeezed and released. Materials that are predominantly silt will show a dull, dry surface upon squeezing, and a glassy wet surface upon releasing the pressure and upon shaking or vibrating the pat. With increasing clay content, this phenomenon becomes less pronounced due to the lower mobility of the pore water.

The criteria used to describe dilatancy based on the manual field test are as follows:

- None: No visible change in the specimen
- Slow: Water appears slowly on the surface of the specimen during shaking and does not disappear or disappears slowly upon squeezing.
- Rapid: Water appears quickly on the surface of the specimen during shaking and disappear upon squeezing.

(b) Dry Strength

A portion of the soil is allowed to dry out completely in air. A cube of soil about ½ inch square is formed and dried and pressed between the fingers. The cubes with very high strength cannot be broken at all, whereas those with very low strength disintegrate completely on gentle pressure. The soil strength is described as medium if the fragment can be reduced to a powder only with a great effort. Those materials with greater dry strengths are predominantly clay. Further, the dried soil cube can be polished on one's fingernail. If the polished surface is shiny, it is indicative of predominantly clay soils, whereas a dull surface indicates silt. The criteria for determining dry strength in the field is as follows:

- o None: The dry specimen crumbles into powder with mere pressure of handling.

- o Low: The dry specimen crumbles into powder with some finger pressure.

- o Medium: The dry specimen breaks into pieces or crumbles with considerable finger pressure.

- o High: The dry specimen cannot be broken with finger pressure. Specimen will break into pieces between thumb and a hard surface.

- o Very High: The dry specimen cannot be broken between the thumb and a hard surface.

(c) <u>Stiffness/Plasticity</u>

A high degree of stiffness and a very smooth smear in the natural state are indicative of high plasticity. The techniques for determining stiffness/ plasticity in the field are described below:

- o Nonplastic: A 1/8 inch (3 mm) thread cannot be rolled at any water content.

- o Low: The thread can barely be rolled and the lump cannot be formed when drier than the plastic limit.

- o Medium: The thread is easy to roll and not much time is required to reach the plastic limit. The thread cannot be rerolled after reaching the plastic limit. The lump crumbles when drier than the plastic limit.

- o High: It takes considerable time rolling and to reach the plastic limit. The thread can be rerolled several times after reaching the plastic limit. The lump can be formed without crumbling when drier than the plastic limit.

(d) <u>Soil Thread Test</u>

This test is an aid in estimating the degree of plasticity and differentiating between organic and inorganic soils. Take a portion of the sample, adding water as necessary, and attempt to roll out on a flat surface with the palm of the hand into threads approximately 1/8-inch in diameter. Fold and repeat procedures until thread begins to crumble into a number of small pieces.

(1)... The fact that a soil can be rolled into threads without crumbling indicates plasticity and the presence of clay. Note the number of times that the process can be repeated. This is indicative of the degree of plasticity; the greater the number of repetitions for fine soils started at the same water content, the more plastic the clay.

(2) As the plastic limit is approached, note the toughness of the threads. Highly plastic, inorganic, fat clays will feel very tough. Leaner, sandy or silty clays will feel weak and will crumble easily. This distinction in the toughness of threads can only be felt when the water content is close to the plastic limit. The criteria for describing toughness based on manual field tests are as follows:

- Low: Only slight pressure is required to roll the thread near the plastic limit. The thread and the lump are weak and soft.
- Medium: Medium pressure is required to roll the thread to near the plastic limit. The thread and the lump have medium stiffness.
- High: Considerable pressure is required to thread to near the plastic limit. The thread and the lump have very high stiffness.

(3) Organic soils and inorganic diatomaceous or micaceous soils will feel very spongy and elastic.

(e) Ball Thread Test

Identification can also be made on the following basis: The soil is molded and water content adjusted until a 1½-inch-diameter ball formed from the soil shows a flattened contact surface of 7/8-inch-diameter when dropped from a height of 2 feet. (Gravel sizes are not included in the ball.) The smallest thread possible without crumbling is then rolled from the above soil sample. The following approximate relationships are then used for identification:

Thread Diameter	Descriptive Term
1/4 inch	SILT, trace clay
1/8 to 1/16 inch	Clayey SILT
1/32 inch	Silty CLAY
1/64 inch	CLAY

(f) Test Tube Test

Silt- and clay-size particles may also be differentiated by determining their approximate settling rates in water. The settling rate may be measured in the field by shaking a small sample of soil in a test tube filled with water and then allowing the particles to settle. The time required for particles to fall a distance of 4 inches is about 30 seconds for 0.074-mm particles (the boundary between sand and silt) and about 50 minutes for 0.005-mm particles (the boundary between silt and clay). An approximate idea of the grain sizes present in a sample of the fine-grained soil may be obtained by this method.

To accurately determine the properties of fine-grained soils, evaluation of Atterberg Limits may be desirable. Atterberg Limits are laboratory procedures used to identify the plasticity of fine-grained soils. Atterberg Limits should be performed according to American Society of Testing and Materials (ASTM) for the liquid limit determination (D 4318-84) and for plastic limit and plasticity (D 4318-84). If Atterberg Limit determinations are made for individual samples, they will be classified according to the plasticity chart shown in Figure 3.5-3.

3.5-3.3 Gradation Designation

A determination of the approximate percentages of various particle sizes in a soil sample is also important. Soil samples can be described as widely graded, uniformly graded, and gap graded. Laboratory gradation tests (ASTM D 422-63) for particle sizes retained on No. 200 sieve can be used to determine the clay and silt content of a sample. Figure 3.5-4 is an example of the various types of grading that can be described in soil samples.

- Widely Graded: a soil sample with a wide range of grain sizes, including a substantial amount of intermediate grain sizes. A glacial till is an example of a widely graded sample. This term is synonymous with poorly sorted. Engineering terminology will describe this as "well-graded."

- Uniformly Graded: a soil sample consisting predominantly of one grain size. A beach sand is an example of uniformly graded sand. This term is synonymous with well sorted. Engineering terminology will describe this as "poorly graded."

- Gap Graded: a soil sample that has a wide range of sample sizes, with some intermediate particle sizes missing. A water-washed till might be gap graded. This term is synonymous with bi-model. Engineering terminology will describe this as "poorly graded".

3.5-3.4 Density/Consistency

Relative density or consistency terms will be used as description modifiers for coarse- and fine-grained soils, respectively.

3.5-3.4.1 Relative Density: Coarse-grained Soils

Relative density descriptors for coarse-grained soils will be based on Standard Penetration Test (SPT) N-Values (ASTM D 1586-84) or a qualitative assessment based on the in-situ sample appearance. The following relative density descriptors will be used:

Relative Density Descriptor	SPT N-Value (Number of Blows/Foot)
Very Loose	0 to 4
Loose	5 to 10
Medium Dense	11 to 30
Dense	31 to 50
Very Dense	51 +

3.5-3.4.2 Consistency: Fine-grained Soils

Consistency descriptors for fine-grained soils can be determined from field tests such as SPT N-Values, or undrained shear strength or unconfined compressive strength data obtained with a torvane or pocket penetrometer. Table 3.5-3 presents field tests that can be performed to determine the consistency of fine-grained soils.

3.5-3.5 Particle Angularity

Particle angularity terms are to be given to coarse-grained soils, as descriptions of the shape of the larger-size, coarse sand and gravel particles and cobbles and boulders. The degree of angularity, while qualitative, is important in evaluating the mode of deposition for the sample recovered. Rounded and subrounded particles might suggest the deposit was waterlaid, whereas subangular to angular particles might suggest the deposit was subjected to abrasion in the deposition. Angularity modifiers (ASTM 1988) to be used are as follows:

- Angular: Particles have sharp edges and relatively plane sides with unpolished surfaces.
- Subangular: Particles are similar to angular description but have rounded edges.
- Subrounded: Particles have nearly plane sides but well-rounded corners and edges.
- Rounded: Particles have smoothly curved sides and no edges.

See also Figure 3.5-5 for classifying particle angularity.

3.5-3.6 Moisture Content

A qualitative judgment of the moisture content of the sample should be noted as soon after recovery of the sample as possible. The determination of soil moisture is important in evaluating ground water levels where piezometric data are insufficient or nonexistent, and in evaluating future behavior of fine soils if excavated or disturbed. The terms (ASTM 1988) to be used for describing moisture content modifiers:

- o Dry: Dry, absence of moisture, dry to touch
- o Damp: No visible water
- o Moist: Little visible water, wet to touch
- o Wet: Some free water visible
- o Saturated: Visible free water, should only be used if 100-percent saturation is to be implied.

3.5-3.7 Structure

The structure of both coarse-grained and fine-grained soils should be carefully observed and is important in identification of depositional environments and in the identification of a local geologic unit. The following descriptive terms should be used:

- o Homogeneous: uniform, non-directional properties of fabric without stratification.
- o Stratified: alternating, horizontal layers of different soils or soil-particle sizes greater than 1/8-inch in thickness.
- o Laminated: repeating, alternate horizontal layers less than 1/8-inch thick in fine-grained soils.
- o Banded: alternate contrasting layers in residual soils.
- o Blocky: cohesive soils that may be broken down into small angular lumps without further degradation.
- o Lens: a body of material that is thick in the middle and thin toward the edges.
- o Root holes: small holes caused by root fibers.
- o Heterogeneous: very irregular structure without definite form.
- o Parting: less than 1/16-inch thick horizontal bed (granular soils).
- o Laminae: 1/16- to 1/2-inch thick bed.
- o Layer: 1/2 to 12 inches thick bed.
- o Stratum: bed that is usually greater than 1 foot thick, but occasionally less (e.g., topsoil).
- o Varves: freshwater lake deposit usually in layers (less than 1 inch) but occasionally in alternating light and dark bands of silt and clay up

to 3 inches thick. Typically implies alternating seasonal deposition in a glacial lake.

- Pocket: small, erratic deposit usually less than 1 foot in diameter.

- Occasional: one or less per foot of vertical thickness.

- Interbedded: applied to strata of soil or beds of rock lying between or alternating with other strata of a different nature (e.g., coarse to fine gravelly sand with interbedded layers of fine sandy silt).

- Stratification: the formation, accumulation, or deposition of materials in layers which can be differentiated on the basis of texture, hardness, cohesion, color, mineralogy, or cementation.

- Mottled: marked with spots or blotches of different color, or shades of color, as if stained.

- Topsoil: the upper most in-situ, nutrient-rich, humic soils, frequently consisting of dark brown loamy silt with trace amounts of sand, gravel, and cobbles, and a pronounced structure of living root fibers.

3.5-3.8 Reaction to Hydrochloric Acid

Calcium carbonate is commonly found in soils as a cementing agent. Dilute hydrochloric acid will react with calcium carbonate displaying no reaction or a weak or strong effervescence depending on the amount of calcium carbonate in the soil. The reaction of the soil to hydrochloric acid should be noted in the field. The following criteria have been established to describe the hydrochloric acid reaction:

- None: No visible reaction
- Weak: Some reaction, with bubbles forming slowly
- Strong: Violent reaction, with bubbles forming immediately

3.5-3.9 Geologic Name

A descriptive geologic term should be assigned to identifiable geologic units, designating their depositional origin, if possible (e.g., alluvial sand, glacial till, or outwash). Place names are used only in the soil classification system and by the Soil Conservation Service. Place names identifying type locations are not assigned to soil classifications by any other system. Some examples of geological terms follow:

- Glacial Till: Material ranging in particle size from silt and clay to boulders, which is neither stratified nor sorted according to size. It is a dense, heterogeneous mass usually lying directly over bedrock. Two different till zones may overlie each other. A less dense, weathered, brownish-gray granular till may overlie a very dense, gray basal till. One or the other units may be missing depending on the environment. A presence or lack of an adjacent marine environment, and type of bedrock, will control the presence or absence of clay-size particles. Various types include ground moraine till, drumlin till, and ablation, lodgement, or flow till.

- Loess: A widespread, homogeneous, unstratified, porous, friable soil consisting predominantly of a loose yellow-brown to rust-brown silt with varying amounts of soft sand, root fibers, and trace amounts of gravel immediately underlying the topsoil. May vary in thickness from a few inches to several feet. Frosted grains suggest deposit by wind.

- Saprolite: A soft, earthy, clay-rich, thoroughly decomposed rock formed in place by chemical weathering of the bedrock.

- Lacustrine: Pertaining to, produced by, or formed in a lake.

- Fluvial: Pertaining to, produced by, or formed in a river.

- Varved: Alternating thin layers of silt and clay ranging in thickness from a fraction of an inch to several inches that represents annual cycles of deposition.

3.5-3.10 Unified Soil Classification (USC) Designation

The Unified Soil Classification (USC) designation should be given for each soil sample. Figure 3.5-2 is a flow chart depicting the procedure for classifying soils. Figure 3.5-6 is a presentation of the USC designation that may be used as a guide. USC designation symbols follow:

- GW: well-graded gravels; gravel-sand mixtures
- GP: poorly graded gravels
- GM: silty gravels; gravel-sand-silt mixtures
- GC: clayey gravels; gravel-sand-clay mixtures
- SW: well-graded sands; sand-gravel mixtures
- SP: poorly graded sands
- SM: silty sand
- SC: clayey sands; sand-clay mixtures
- ML: silts; silty, very fine sands or clayey silts
- CL: clays of low to medium plasticity; silty, sandy, or gravelly clays
- CH: inorganic clays of high plasticity; fat clays
- MH: plastic silts; micaceous or diatomaceous silts

- OL: organic silts and organic silty clays of low plasticity

- OH: organic clays of medium to high plasticity

3.5-3.11 Special Conditions or Notes

During the sampling process, observations made which may be of importance in the overall sample identification, should be noted after the sample description. Items such as sample disturbance and foreign substances (e.g., bricks, mortar, or other substances which may indicate filled material or contamination) should be noted with the sample description. Separate measurements for contaminants should be made and recorded separately beside the sample description in the field log.

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SECTION 3.5 SOIL CLASSIFICATION

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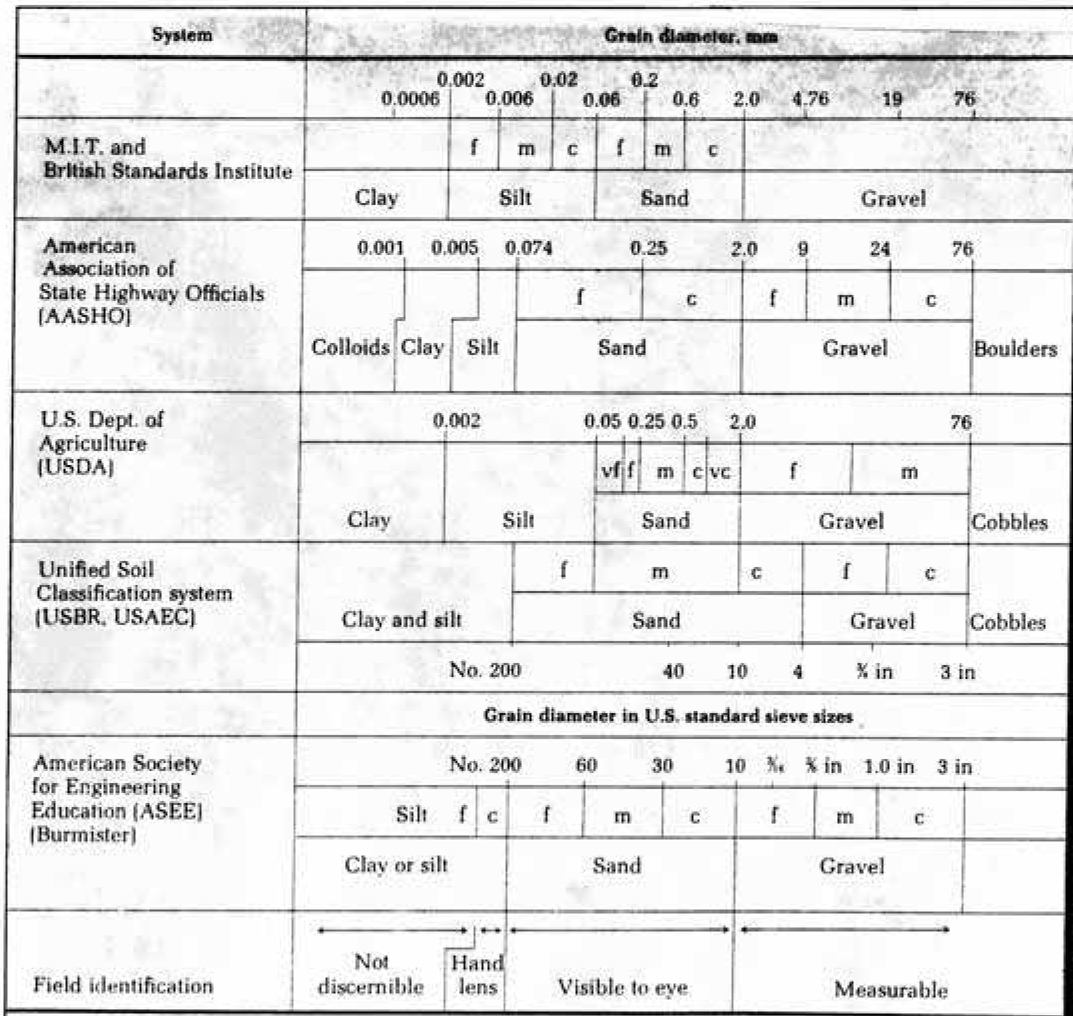


Source: Hunt (1984)

Figure 3.5-1

Soil Classification Systems Based on Grain Size.

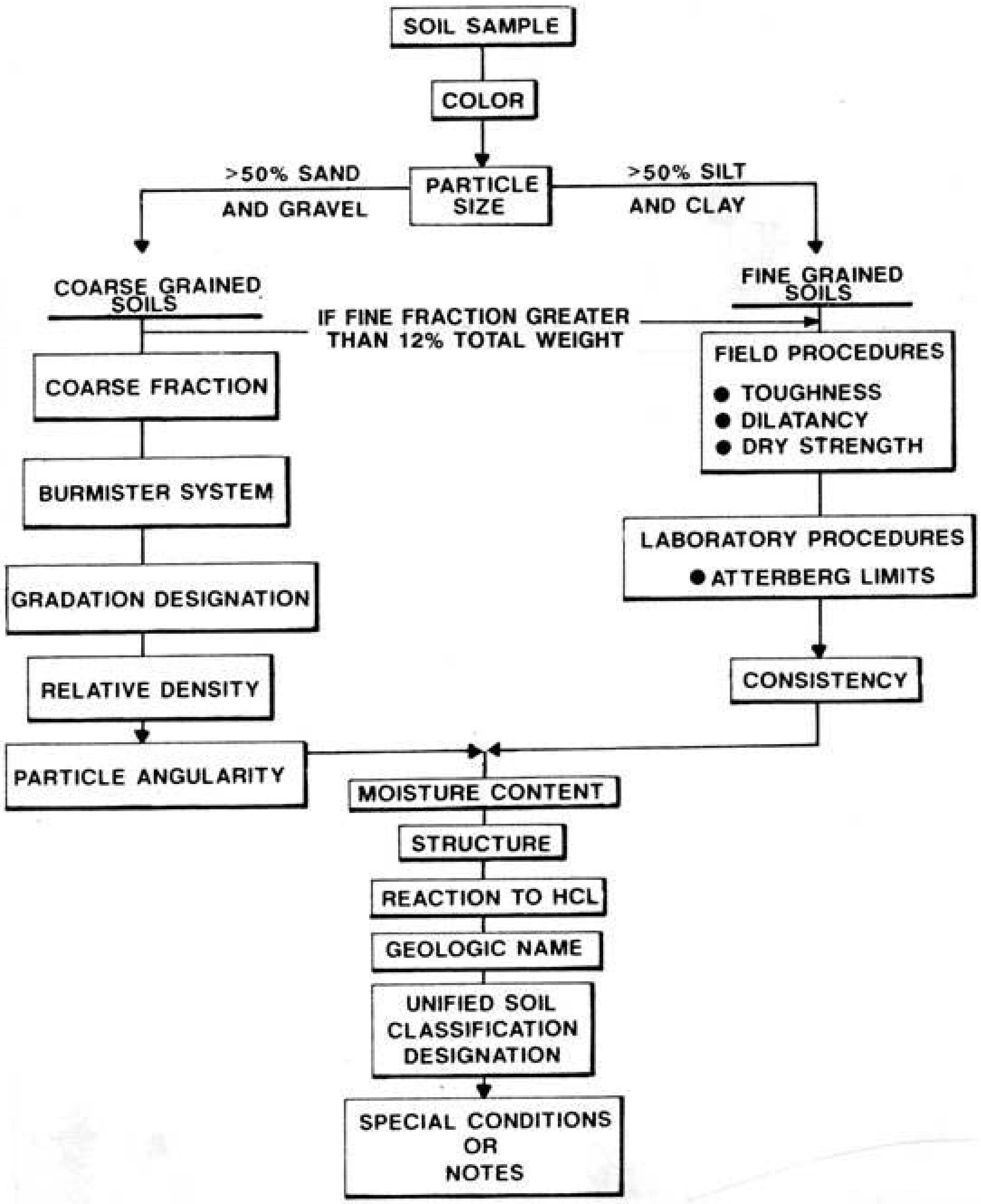
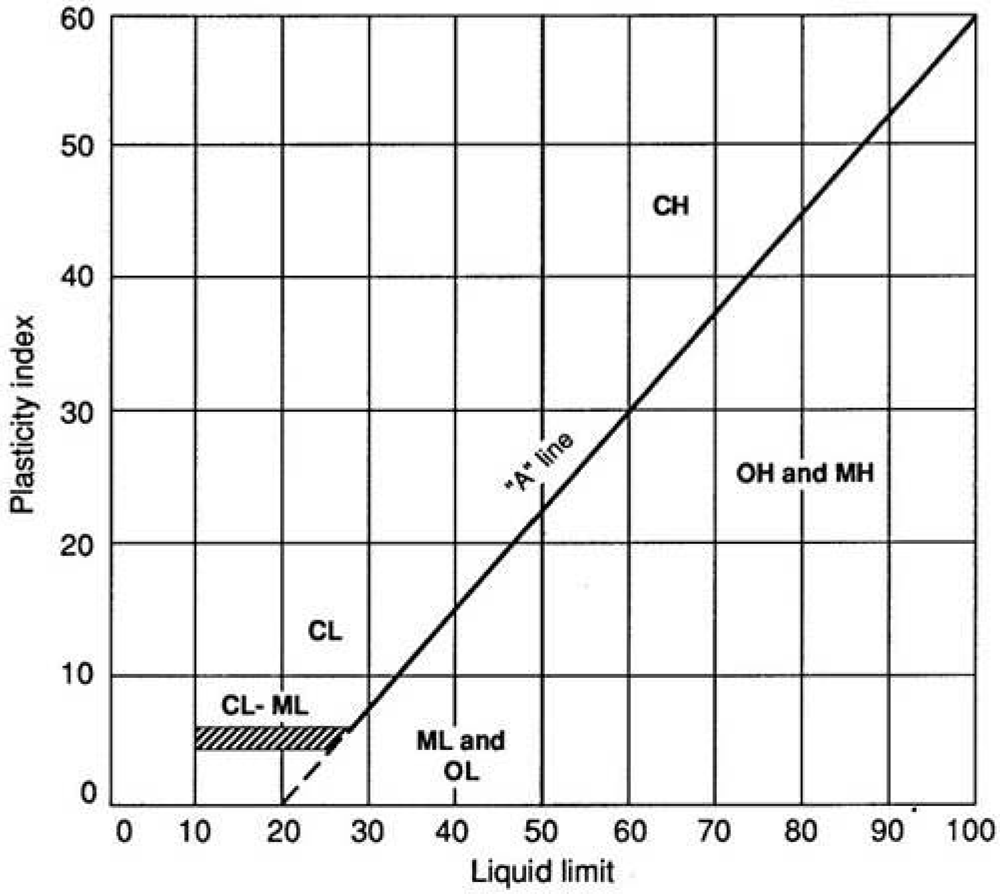


Figure 3.5-2

Soil Classification Flow Chart.

Source: MADEP

Plasticity Chart

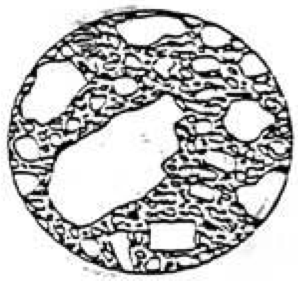


CH = Inorganic Clay - high plasticity
CL = Inorganic Clay - low to medium plasticity
MH = Inorganic Silt - elastic silt
ML = Inorganic Silt - slight plasticity
OH = Organic Clays - medium to high plasticity
OL = Organic Silts - low plasticity

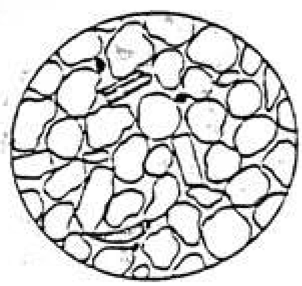
Figure 3.5-3

Plasticity Chart

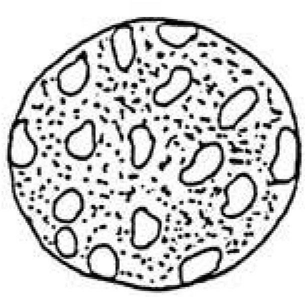
Source: Winterkorn et al. (1975)



**WIDELY GRADED
(Poorly Sorted)**



**UNIFORMLY GRADED
(Well Sorted)**

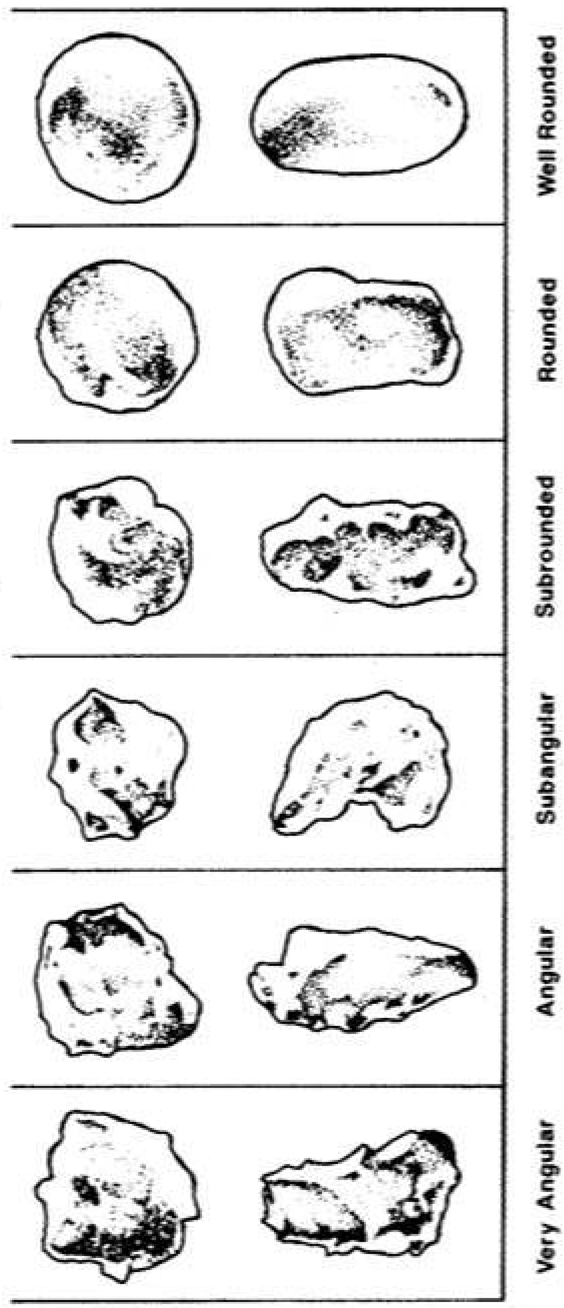


**GAP GRADED
(Bi-Model)**

Source: Modified After Compton (1962)

Figure 3.5-4

Gradation Designation.



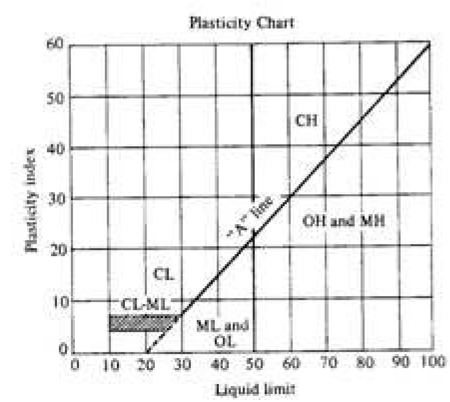
Source: Compton (1985) after Powers (1953)

Figure 3.5-5

Particle Angularity.

Major Divisions			Group Symbols	Typical Names	Laboratory Classification Criteria	
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	Clean gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	Not meeting all gradation requirements for GW	
		Gravels with fines (Appreciable amount of fines)	GM[a] d / u	Silty gravels, gravel-sand-silt mixtures	Atterberg limits below "A" line or P.I. less than 4	Above "A" line with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols
			GC	Clayey gravels, gravel-sand-clay mixtures	Atterberg limits below "A" line with P.I. greater than 7	
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines	$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			SP	Poorly graded sands, gravelly sands, little or no fines	Not meeting all gradation requirements for SW	
		Sands with fines (Appreciable amount of fines)	SM[a] d / u	Silty sands, sand-silt mixtures	Atterberg limits above "A" line or P.I. less than 4	Limits plotting in hatched zone with P.I. between 4 and 7 are *borderline* cases requiring use of dual symbols
			SC	Clayey sands, sand-clay mixtures	Atterberg limits above "A" line with P.I. greater than 7	
Fine-grained soils (More than half material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50)		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	Plasticity Chart (see below)	
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays		
			OL	Organic silts and organic silty clays of low plasticity		
	Silts and clays (Liquid limit greater than 50)		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts		
			CH	Inorganic clays of high plasticity, fat clays		
			OH	Organic clays of medium to high plasticity, organic silts		
	Highly organic soils		Pt	Peat and other highly organic soils		

Determine percentages of sand and gravel from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows:
Less than 5 per cent — GW, GP, SW, SP
More than 12 per cent — GM, GC, SM, SC
5 to 12 per cent — *Borderline* cases requiring dual symbols[b]



Source: Winterkorn et al. (1975)

Figure 3.5-6

Unified Soil Classification System.

NAME	SIZE LIMITS (SIEVE SIZES)	FAMILIAR REFERENCE
Boulders	12 inches or more	Basketball or larger
Cobble	3 to 12 inches	Softball
Coarse Gravel	3/4-inch to 3 inches	Baseball
Fine Gravel	No. 4 Sieve to 3/4-inch	Pea
Coarse Sand	No. 10 to No. 40 Sieve	Rock Salt
Medium Sand	No. 40 to No. 10 Sieve	Sugar, Table Salt
Fine Sand	No. 200 to No. 40 Sieve	Powdered Sugar
Silt and Clay	Less than No. 200 Sieve	Flour

Table 3.5-1

Particle Size Identification Based on Unified Soil Classification System.

Source: Hunt (1984)

Component	Written	Descriptor	Percentage Range by Weight
Principal	Capitals		> 50 percent
Minor	Lower Case	and	35 to 50
		some	20 to 35
		little	10 to 20
		trace	0 to 10

Source: Hunt (1984)

Table 3.5-2

Burmister System Desciptors Suitable for Estimating the Distribution of Gravel-, Sand-, and Silt-size Particles.

DESCRIPTION	CRITERIA
Very Soft	Extruded between fingers
Soft	Molded by slight pressure
Medium (firm)	Molded by strong pressure
Stiff	Indented by thumb
Very Stiff	Indented by thumbnail
Hard	Difficult to indent

Consistency Descriptor	SPT N-Value	Undrained Shear Strength (tsf)*	Unconfined Comp. Str. Descriptor (tsf)*
Very Soft	<2	<0.10	<0.25
Soft	2 to 4	0.10 to 0.25	0.25 to 0.50
Medium (firm)	4 to 8	0.25 to 0.5	0.50 to 1.0
Stiff	8 to 15	0.5 to 1.0	1.0 to 2.0
Very Stiff	15 to 30	1.0 to 2.0	2.0 to 4.0
Hard	>30	>2.0	>4.0

* Tons per Square Foot

Source: Hunt (1984)

Table 3.5-3

Criteria for Describing Consistency Based on Field Tests.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 3.6 IN-SITU SAMPLING OF ROCK

SECTION 3.6
IN-SITU SAMPLING OF ROCK

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SECTION 3.6 IN-SITU SAMPLING OF ROCK

3.6-1 PURPOSE

Environmental assessments at contaminated sites often require the determination of the presence of chemical contamination in bedrock and the extent to which the contamination can migrate in the rock mass. Hydrogeological assessments for water supply purposes require a thorough understanding of the competency of the bedrock and its water quality. To assess the presence and potential for fluid migration in rock, samples of the rock mass must be obtained for visual and laboratory analysis. These analyses will yield the following characteristics of the rock, which are necessary for classification:

- lithology
- mineralogy
- structure
- weathering
- hardness
- permeability

Methods of sampling rock for environmental assessments include the following:

- surface rock sampling
- rock core sampling

Field mapping of exposed bedrock (outcrops) is usually the first step in a site investigation. Field mapping is limited to a description of the near-surface bedrock type and conditions, and this method is often severely hampered in New England due to the limited number of exposures in glaciated regions. Consequently, surface mapping is often supplemented with subsurface investigations (i.e., drilling and logging of bedrock borings). Drilling bedrock borings has an added advantage in that it provides data on how the bedrock conditions change with depth. Typically, monitoring wells are installed in these borings to obtain hydrogeologic data. Generally, a thorough hydrogeologic or geotechnical field investigation incorporates all three methods to adequately characterize the bedrock conditions at the site.

This Standard Reference (SR) presents devices/equipment and techniques for the collection of both surface and subsurface rock samples. While many sampling devices are available to collect rock samples, this section provides SRs for only those most commonly used in environmental assessments. Other equipment commonly used for traditional geotechnical engineering studies are listed without detailed SRs.

3.6-2 SURFACE ROCK SAMPLING

3.6-2.1 Methodology

Sampling the rock surface can be done manually with picks and hammers or other probing devices, or with a mechanized excavator (e.g., a backhoe). The depth of sampling is limited by the ability of the equipment to penetrate the rock surface.

3.6-2.2 Procedure

1. Sketch the area to be sampled noting the following:

    - orientation of rock structure
    - orientation of sample site to other physical features
    - areas of observed contamination, if any

2. Obtain a sample of rock using equipment capable of breaking a piece of the rock mass. The equipment used will be decontaminated in accordance with the protocols established in the project plans, if necessary.

3. Log and classify the rock sample in accordance with Section 3.7 Rock Classification.

Advantages

- Inexpensive method to obtain several surficial samples.
- A larger surface of the rock is available for inspection and measurement of fracture and foliation patterns.

Disadvantages

- Only shallow samples can be obtained.
- Limited to outcrops or areas where the bedrock surface can be exposed.
- Limited information regarding the rock mass.
- Increased potential for worker exposure to contaminants, if present where samples are obtained.

3.6-3 ROCK CORE SAMPLING

3.6-3.1 Sampling Equipment

The primary objective of rock core sampling is to obtain a continuous sample of the intact rock mass to allow determination of the geologic and engineering properties of the rock. In addition to collection of rock samples, the completed rock-core borehole may be tested and monitored to determine permeability, in-situ stresses, orientation and openness of discontinuities, ground water conditions, the presence of gas, and squeezing or expansive properties of the rock. The borehole may be further utilized for in-situ testing purposes, borehole geophysical surveys, and the installation of various types of monitoring equipment or instrumentation.

Rock core is obtained with a core barrel sampling device. The primary purpose of the core barrel is to recover in a relatively undisturbed state the total length of rock that has been physically cored. When drilling in competent rock, total recovery is rarely a problem; however, when the formation is highly weathered, fractured, or soft, core recovery becomes more troublesome. The strength and behavior of the rock mass is primarily dependent on various inherent discontinuities; core that is not recovered may be the result of such factors, which might represent significant environmental implications.

Selection of the most practical core barrel for the anticipated bedrock conditions is important. Selection of the correct drill bit is also essential to good recovery and drilling production. Selection of the diamond size, bit crown contour, and number of water ports is dependent on the characteristics of the rock mass. The use of an incorrect bit can be detrimental to the overall core recovery. Generally, fewer and larger diamonds are used to core soft formations. Smaller diamonds mounted on the semiround bit crown are used in hard formations. Special impregnated diamond core bits have been developed for use in severely weathered and fractured formations where bit abrasion can be very high. Different types of core bits are shown in Figure 3.6-1. Table 3.6-1 shows the standard sizes of diamond core bits and wireline. W.L. Acker III summarizes drilling equipment and bits in Chapters 10 and 11 of "Basic Procedures for Soil Sampling and Core Drilling" (1974). Core barrels to be considered for use in environmental assessments include the following:

- o double-tube core barrel (Section 3.6-3.1.1)
- o triple-tube core barrel (Section 3.6-3.1.2)
- o wireline core barrel (Section 3.6-3.1.3)
- o oriented-core equipment (Section 3.6-3.1.4)

Other rock coring equipment occasionally used for geotechnical engineering studies include the following:

- o shot-core barrel (Section 3.6-3.5.1)
- o steel-tooth cutter barrel (Section 3.6-3.5.2)
- o percussion core barrel (Section 3.6-3.5.3)
- o single-tube core barrel (Section 3.6-3.5.4)
- o integral sampling method (Section 3.6-3.5.5)

However, such equipment/methods are not used for environmental assessments; therefore, SRs are not provided in this section. A brief description of these items is included in Section 3.6-3.5.

The following subsections describe the rock core sampling equipment and associated advantages and disadvantages for the equipment most commonly used for environmental assessments.

3.6-3.1.1 Double-tube Core Barrel

The most widely used rotary-core barrel is the double-tube. It is a single-tube barrel containing a separate and additional inner tube. It is available with either a rigid or swivel-type inner tube construction (Figure 3.6-2). In the rigid types, the inner tube is fixed rigidly to the core barrel head so that it rotates with the outer tube. In contrast, the swivel-type inner liner is supported on a ball-bearing carrier, which allows the inner tube to remain stationary (or nearly so) during rotation of the outer barrel. The sample or core is cut by rotation of the diamond bit. The bit is in constant contact with the drilling fluid as it flushes out the borehole cuttings. The addition of bottom discharge bits and fluid control valves to the core barrel system minimizes the amount of drilling fluid and its contact with the sample, which further decreases sample disturbance.

The swivel-type, double-tube core barrel or equivalent is the preferred type of double-tube core barrel for environmental assessments. This core barrel has a nonrotating, adjustable, chrome-plated inner liner that is available in either solid- or split-tube versions. The split-tube version is preferred for environmental assessments.

Depending on the quality of the rock being cored, the inner tube may be alternately used in the solid or split inner modes. The solid tube is used primarily in very sound and competent portions of the rock, while the split tube is used in the weaker and more weathered portions.

The design of the split inner tube allows expansion of the two liner halves during the core recovery process. This feature allows swelling clays or highly fractured material, which could normally block a conventional solid liner, to move up into the chrome-plated liner, reducing blockage of the core and improving recovery in lower-quality rock. This expansion feature, however, limits its usefulness in wireline systems. Wireline systems utilize a rope made of steel wires. This steel rope (wireline) in used, to hoist drill pipes, and drilling tubes up the inside of the bore hole.

An additional and major advantage of the split tube is apparent during subsequent surface handling of the recovered core. The inner tube is easily removed from the core barrel, and the filament tape that binds the liner halves together is cut, separating the two sections and exposing the recovered core in a nearly in-situ state. This design feature of the split liner eliminates the necessity of "banging out" the core sample with a hammer, as is frequently done with a conventional solid tube. Such core removal may severely disturb and alter the quality of the recovered core, potentially leading to erroneous conclusions about the overall rock mass.

The split inner tube is used in various types and sizes of double-tube core barrels. The capability of improving recovery in poor-quality rock and the subsequent surface handling advantages make it a valuable addition to the equipment for rock core evaluation.

Advantages

- Widely used.
- May block less frequently than solid tube.
- Improved recovery over single-tube barrel.
- Suitable for highly fractured or weathered rock.
- Less disturbance of the rock core compared to a single-tube barrel.
- Provides an opportunity to view the core in its "as drilled" state when the barrel is opened.

Disadvantages

- Not suitable for wireline systems.
- More complex and difficult than the single-tube core barrel to decontaminate, if necessary.

3.6-3.1.2 Triple-Tube Core Barrel

The triple-tube core barrel adds a separate, nonrotating liner to the double-tube core barrel inner tube. This liner, which retains the sample, consists of a clear plastic solid tube or a split, thin metal liner. Each type of liner has its distinct advantages and disadvantages; however, they both have the advantage of minimizing sample handling and disturbance during removal from the core barrel.

The NWM3 triple-tube core barrel, manufactured by Acker Drill Co., Inc., is an example of a double-tube core barrel modified to include an additional (third) inner, solid, clear plastic liner, which retains the sample.

The purpose of the third, nonrotating inner liner is to provide a temporary storage container for the recovered rock core during transportation and storage. The NWM3 incorporates an adjustable inner liner that can control the flow of water to the bit, an important design feature in variable formation conditions. Triple tube systems yield smaller core sizes than double tube systems of the same letter designation because more room is taken up by the extra tube.

A special hydraulic or pneumatic jack is required for inner tube removal and subsequent sample extraction from the inner tube. Although the solid plastic sample liner tube has definite advantages during transportation and storage, it can impede field examination, photography, and evaluation of the core immediately upon recovery.

Advantages

- May improve core recovery of poor-quality rock compared to single-tube core barrel.

- Core can be seen in its "as drilled" state when the barrel is opened in the laboratory - important in highly fractured or weathered rock.

Disadvantages

- Large number of components require more time to decontaminate, if necessary, than single-tube barrels.

- Potential for jamming of the rock core.

- Core not readily available for field examination.

3.6-3.1.3 Wireline Core Barrel

In conventional rock coring, the entire drill stem and core barrel must be removed after each core run. This is a time-consuming operation in deep boreholes; in addition it creates an inherent risk of collapse of the rock into the unsupported borehole. The wireline system is designed to recover rock core without removing the drill stem from the borehole after each core run. An illustration of a wireline core barrel assembly is shown in Figure 3.6-3.

When drilling is completed, a special latching mechanism is attached to the end of a cable and lowered through the drill rods; it attaches to the inner tube head of the core barrel. The inner tube, containing the rock core, is rapidly brought to the surface, leaving the outer core barrel and drill rods still in position within the borehole. The wireline can also be adapted for horizontal drilling and triple-tube applications.

Advantages

- Reduces time to retrieve the rock core sample in deep boreholes.
- Borehole remains supported for entire length.

Disadvantages

- Is more time consuming if borehole is less than 50 feet deep.

- Special inner core tube and special latching mechanism are expensive to rent or purchase.

- Large number of parts discontinued.

3.6-3.1.4 Oriented Core Equipment

Determination of the true attitudes of planar structural discontinuities of rock encountered during subsurface explorations may be accomplished in two ways: (1) by measuring the azimuth and dip of the discontinuities recorded on the physical core recovered; or (2) by determining the orientation of the structural features from their presence on the borehole wall. This information is of particular importance to the engineering geologist and geotechnical engineer. Although not frequently used for environmental assessments because of cost, it can be strategically used to provide cost-effective information on the orientation of rock mass discontinuities and their influence on contaminant migration.

Various methods, ranging from simple to complex, have been developed to establish a reference point of known orientation so that all structural aspects of the borehole may be related to it and their absolute orientations determined. The Integral Sampling Method is one of the more complex methods of achieving structural orientation of the in-situ rock and total rock core recovery. The most frequently used equipment are orienting core barrels, which combine conventional rotary rock drilling equipment with specialized core barrels that mark the core so that it can be subsequently oriented using geologic interpretive methods.
Other techniques and equipment available but not considered suitable for most environmental assessments include paint and acid markers, Craelius core orientator and physical core alignment methods. The latter includes the following:

(a) Orienting Core Barrel

Specialized core barrels have been developed that scribe a reference mark on the core as it is drilled. Special recording devices within the core barrel relate known azimuth orientations to the reference mark so that when the core is subsequently removed from the core barrel, it can be oriented to the position it occupied in-situ.

(b) BHP Orienting Core Barrel

The BHP core barrel, developed by Broken Hill Proprietary Co. of Australia, utilizes a compass and chart recording system that aligns itself with a scribing diamond. As the core passes the drill bit into the inner liner, a reference line of known orientation is scribed on the rock core.

(c) Christensen-Hugel Orienting Core Barrel

Operation of the C-H core barrel, developed and patented by the Christensen Diamond Products Co., is similar to that of the BHP barrel. Incorporated within the core barrel is an Eastman multi-shot directional survey instrument that photographically records the compass bearing and plunge of the borehole. In addition, it records the orientation of reference grooves that are cut into the core as it enters the barrel.

Advantages

- o Determines actual orientation of rock discontinuities.

Disadvantages

- o Very expensive.
- o Requires staff experienced in its use.
- o Good recovery is required for accurate interpretation.
- o Will not function in strongly magnetic environments.

3.6-3.2 Rock Coring Procedure

1. Advance the borehole to the rock surface using the techniques described in Section 3.2 Drilling Techniques.

2. Firmly seat the casing into the bedrock surface to seal off the borehole from the overlying strata and flush the borehole is with clean water.

3. Carefully inspect the core barrel to ensure that all equipment is operating properly. If necessary, decontaminate the core barrel in accordance with the project plans.

4. Select bit types to produce the optimum recovery of each type of rock to be cored. It may be desirable to change bits depending on the rock types encountered. When production drops worn out or damaged bits must be changed.

5. Lower the core barrel into the borehole and connect the drill stem to the drill rig.

6. Use potable water the drilling fluid unless an alternate source has been approved by DEP and is identified in the project plans. No exceptions are allowed if the bedrock to be cored is an identified aquifer. Test the water source if chemical samples are to be obtained later from the borehole or the monitoring well.

7. Place marks between 1 and 6 inches apart on the slide piston to monitor the rate of advancement of the core barrel.

8. Advance the core barrel by controlling the rate of feed, rotation speed, and flow of drilling fluid. To minimize core losses in soft, erodable rock, the following measures are recommended:

   - o Restrict drilling to short runs of 2 to 3 feet each.

   - o Keep drilling water pressure low (under 150 pounds per square inch [psi].)

   - o Keep feed pressure under 100 psi.

- o Use a split inner core barrel.

9. Screen return water for volatile organic compounds (VOCs) using an organic vapor analyzer.

10. Once the core barrel is advanced to the required depth or progress stops as a result of a blockage, stop the rotation, terminate the circulation of drilling fluid, and raise the drill stem a few inches to break the rock core from the rock mass.

11. Retrieve the core barrel. The drill rods and core barrel must be screened using an organic vapor analyzer as they are removed from the borehole.

12. Open the core barrel, observe and log the core, and place the recovered rock core in rock core boxes. If the drilling is taking place in a contaminated area, scan the core with an organic vapor analyzer. Details regarding rock core handling and logging are discussed in the next subsection (Sections 3.6-3.3 and 3.6-3.4).

13. Repeat steps 5 through 12 until the desired depth is achieved. When drilling in a contaminated area, a decontaminated core barrel must be used.

14. Split-spoon drive samples may be taken in any zones where it is not possible to drill and obtain satisfactory recovery of soft erodable rocks. Satisfactory recovery for this purpose is defined as 50 percent or greater.

The inspecting geologist must not permit a full coring run to be drilled if he/she suspects that residual core was left in the hole on the previous run. If this is believed to have occurred, he/she should direct that the next coring run be shortened by the length of core believed to have been left in the hole. This is necessary to prevent blocking the core barrel, grinding of the core and splitting open split-tube core barrels.

3.6-3.3 Sample Handling and Storage

Upon removal of the core barrel from the drillhole, wash the core while it rests in the liner half if a split tube has been used. Care must be used in washing to avoid removing small pieces of core or soft joint or vein fillings. If the rock is soft, friable, or otherwise erodable, and, in the opinion of the inspecting geologist, washing will damage the core, the washing process may be omitted.

Place the core in wooden boxes specially constructed to hold and store rock cores (Figure 3.6-4). Place the core in the core box with the top of the run at the upper left corner; place the remaining core sequentially from left to right and from the rear (nearest the cover hinge) of the box to the front. If a split tube has been used, transfer the core to cardboard or plastic half-rounds prior to placement in the box.

Place wood blocks marked with the appropriate depth and run number between each separate core run. In addition, wherever core is lost due to the presence of a cavity or large joint (open or filled), place a spacer block in the proper relative position in the core box. The spacer is the same length as that of the lost core. Mark the depth range on the spacer along with the reason for the missing core (e.g., cavity or large joint).

Mark the core box on the top and both ends with the project name, site identification, boring number, depth range, and box number. The Rock Quality Designation (RQD) should be indicated on all core boxes.

3.6-3.4 Logging Rock Cores

The basic objective of describing rock cores is to provide a concise record of important geologic and physical characteristics of the rock core (e.g., rock type/name, lithological/structural features, any physical conditions, including alteration, and any special geologic, mineralogic, or other features pertinent to interpretation of the subsurface conditions).

Drill core of some rock types change (sometimes rapidly) once removed from its natural environment. These can be a change in physical properties on exposure to air, often aggravated by physical degradation of the core due to rough handling. It is, therefore, advisable to do all the logging immediately at the drill site. Note all physical changes that the core incurs; therefore, look at and possibly relog all cores that have been exposed to the air for some time. Note effects on the physical properties of the rock (e.g., slaking action or effects of melting of frost or ice). This will give some indication of the long-term behavior of the material once it is exposed to the atmosphere.

Personnel who handle diamond-drill core must avoid rough handling. Sampling should be done with the minimum possible destruction of the core. Permanently store core in a well-protected shelter or core shack. Depending on the situation, it is often advisable to photograph the core at the drilling site before it is transported or damaged. Photographs provide an inexpensive permanent record of the core and may prove valuable at a later date for general lithological, fracture density, and rock quality assessments, as well as for pictorial documentation in reports and evidence during litigation.

3.6-3.4.1 Geologic Core Log

The geologic borehole core log should contain a systematic description of lithological characteristics of each rock type encountered, using the procedures provided in Section 3.7 Rock Classification. Include a graphic or symbolic log. Typical borehole core logs are shown in Figures 3.6-5 and 3.6-6.

The structural part of the log should contain details on major and minor structures and information on mechanical properties of the rock. Log both descriptively and graphically any discontinuities in the core. Record all relevant geologic structural features in the core logger

Recognition of the generic type of discontinuity may not be possible in the core. The logger should be concerned with mapping only naturally occurring discontinuities. Do not record any cracks or irregular fractures caused by poor coring and handling techniques. Special effort should be made to familiarize the logger with the difference between induced and naturally occurring fractures in the core.

The mechanical properties of the rock core can be assessed in terms of core recovery, RQD, hardness, weathering, strength, and fracture density to indicate the variation in rock quality.

3.6-3.4.2 Logging Procedures

Note the following features for all rock types:

- Rock type description (see Section 3.7).
- Attitude of bedding, cleavage, or foliation planes, and the ease of splitting along such planes.
- Attitude and degree of jointing, whether open or filled, as well as evidence of shearing, crushing, or faulting.
- Degree of alteration or weathering, hardness of the rock, and other engineering properties.
- RQD for NQ or larger-size cores.

3.6-3.4.3 Rock Quality Determination (RQD)

The RQD (Deere, 1964) method of determining rock quality is as follows:

1. Sum the total lengths of core fragments, counting only those pieces of core that are 4 inches (10 cm) in length or longer (as measured along the vertical axis) and are hard and sound. If the core is broken by handling or by the drilling process, the fresh broken pieces are fitted together and counted as one piece, provided they form the requisite length of 4 inches (10 cm).

2. The RQD is represented as a percentage. The percentage is derived by dividing the total sum of core pieces (4 inches or greater) by length of the run minus the length of the core left in the hole times 100. See equation below:

$$RQD = \frac{\sum L(>4")}{(R-C)} \times 100$$

Where: $\sum L(>4")$ = Sum of total length of core pieces 4 inches or greater
R = Length of total core run
C = Length of core left in borehole

Below is a table relating the RQD percentage to a qualifier word for use in the well logs when coring in bedrock.

RELATION OF RQD AND ROCK QUALITY

RQD (%)	Description of Rock Quality
0 to 25	very poor
25 to 50	poor
50 to 75	fair
75 to 90	good
90 to 100	excellent

NOTE: RQD can only be used on NQ core or larger. The RQD should always be shown on the core log as a percentage.

3.6-3.4.4 Documentation

All descriptive data shall be noted on the geologic core log by the geologist responsible for core logging. All completed boring logs shall be reviewed by a qualified geologist to assure completeness and technical accuracy. Any changes, additions, or deletions to the original field logs shall be made so that the original entry (words and/or numbers) remains legible. Under no circumstances will any erasures be allowed. If extensive deletions and additions are necessary, a second boring log form may be attached to the original and labeled with the original sheet number and a small "a" after said number. Upon completion of the review, the supervising geologist will initial and date the "Checked By" section of the boring log. All documentation originals shall remain in the project files.

3.6-3.4.5 Logging Equipment

The following equipment is used for geologic core logging:

- water supply for wetting core
- timepiece
- wooden core boxes (standard size) with wood blocks and hinged lids
- markers (indelible felt tip)
- labels
- acid bottle (dilute hydrochloric acid)
- pocket knife
- protractor (clear)
- magnifying hand lens
- collapsible, 6-foot folding ruler (marked in tenths)
- tape, 100-foot length (marked in tenths)
- sounding device
- reference materials and forms
- field notebook (waterproof) with a supply of pencils and pens
- camera (optional)
- Schmidt hammer (optional)
- point load tester (optional)

3.6-3.5 Other Specialty Core Barrels

Other types of specialty core barrels not normally used for environmental assessments include the following:

- calyx or shot-core barrel
- steel-tooth cutter barrel
- percussion core barrel
- single-tube core barrel

Because these types of core barrels are not commonly used, only a brief description of each type follows and advantages and disadvantages of each will not be included.

3.6-3.5.1 Calyx or Shot Core Barrel

This device, used to obtain large-diameter samples of competent rock core, derives its name from the use of chilled, hard steel shot as the cutting medium. Single-tube, heavy-walled, soft-steel cutter barrels of varying lengths and diameters are manufactured by Ingersoll-Rand Co. especially for this purpose. The steel shot is fed into the annular space between the core and core barrel and grinds its way to the bottom of the barrel. The steel shot, which is added as the drilling progresses, wears away the rock beneath the rotating barrel. A special "calyx" at the top of the barrel causes a reduction in the rate of the returning wash water and serves to collect the borehole cuttings and worn-out shot.

The core is removed from the borehole by a special large-diameter core lifter or by grouting the core inside the barrel with gravel. Considerable driller expertise is required with this method. The diameter of the core that can be recovered is limited only by the capability of the equipment to turn the core barrel and subsequently recover it.

3.6-3.5.2 Steel-tooth Cutter Barrel

Single-tube core barrels equipped with metal teeth are used for obtaining large-diameter cores in soft or seamy rock. However, any type of core barrel may be equipped with steel cutter teeth if the situation does not require the use of diamond bits. The Denison and Pitcher samplers discussed in Section 3.4 In-situ Sampling of Soil are generally equipped with this type of cutter bit. The steel cutter teeth may also be equipped with hard metal alloy inserts (e.g., tungsten-carbide) to improve drilling rates. The metal inserts may be replaced in the bit very readily, renewing a dull or damaged bit for additional drilling.

The steel-tooth cutter barrels are operated in the same manner as conventional rotary core barrels, except that they are rotated at much slower speeds.

3.6-3.5.3 Percussion Core Barrel

This core barrel consists of an outer barrel with a hardened steel bit and an inner barrel equipped with a pressure-release system and core retainer. The inner barrel remains in contact with the rock and slides down over the core as the surrounding material is cut away by raising and dropping the outer barrel.

Cores can be obtained in materials ranging from partially cemented soils to medium-hard rock. However, some disturbance and breakage of the core usually occurs during the dynamic sampling process.

3.6-3.5.4 Single-tube Core Barrel

The simplest type of rotary-core barrel is the single tube, which consists of a case-hardened, hollow steel tube with a diamond drilling bit attached at the bottom. The diamond bit cuts an annular groove or kerf in the formation to allow passage of the drilling fluid and cuttings up the outside of the core barrel. However, the drilling fluid must pass over the recovered sample during drilling; the single-tube core barrel cannot be employed in formations subject to erosion, slaking, or excessive swelling. Although the single tube is a very rugged core barrel and easy to operate, its limitations during sampling of both soil and rock are contributing to its declining application.

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SECTION 3.6
IN-SITU SAMPLING OF ROCK

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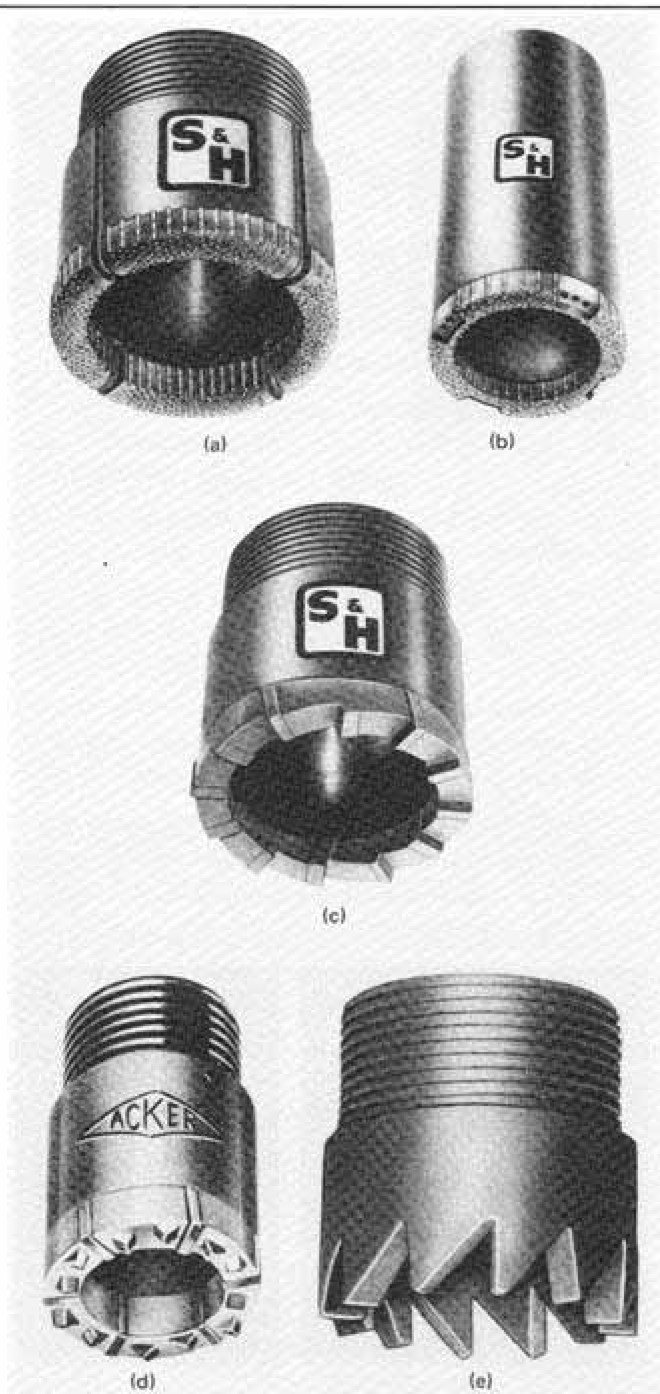


(a) (b)

(c)

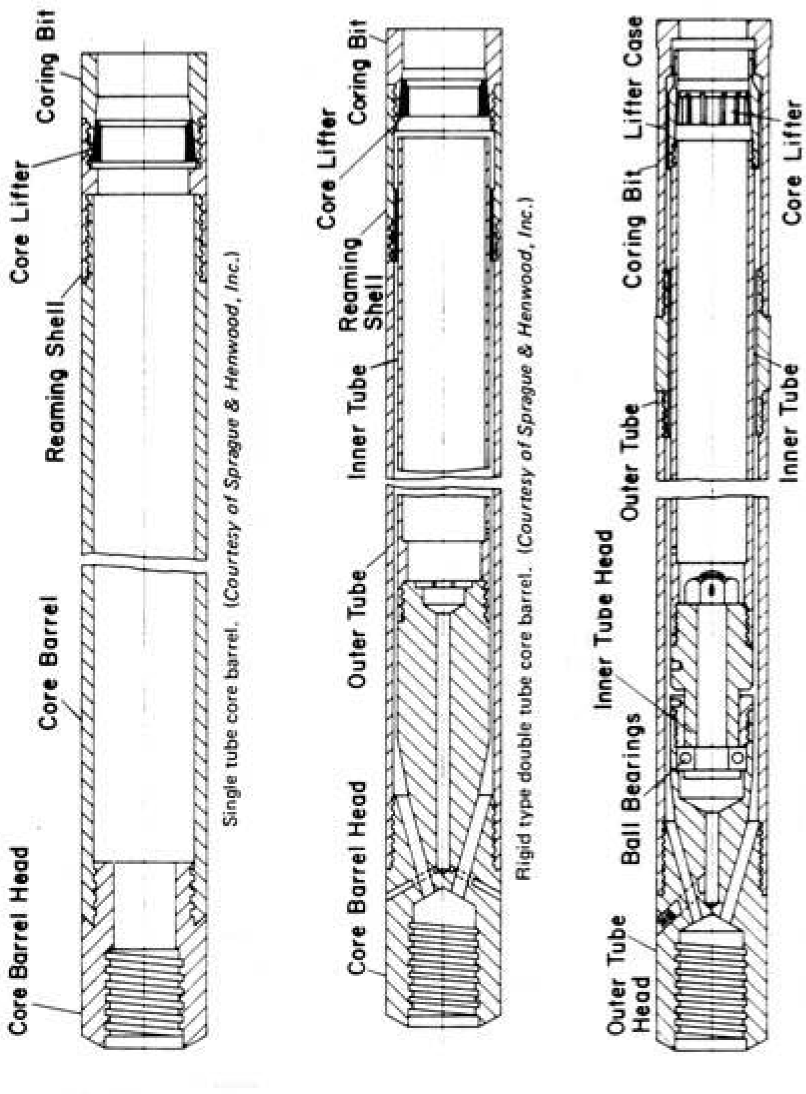
(d) (e)

Fig. 1.36 Coring bits: (a) diamond with conventional waterways; (b) diamond with bottom discharge waterways; (c) carbide insert, blade type; (d) carbide insert, pyramid type; (e) sawtooth. *(Courtesy of Sprague & Henwood, Inc. and Acker Drill Co., Inc.)*

Source: Winterkorn et al. (1975)

Figure 3.6-1

Different Types of Core Bits.



Single tube core barrel. (*Courtesy of Sprague & Henwood, Inc.*)

Rigid type double tube core barrel. (*Courtesy of Sprague & Henwood, Inc.*)

Source: Winterkorn et al. (1975)

Figure 3.6-2

Single-and Double-tube Core Barrels.

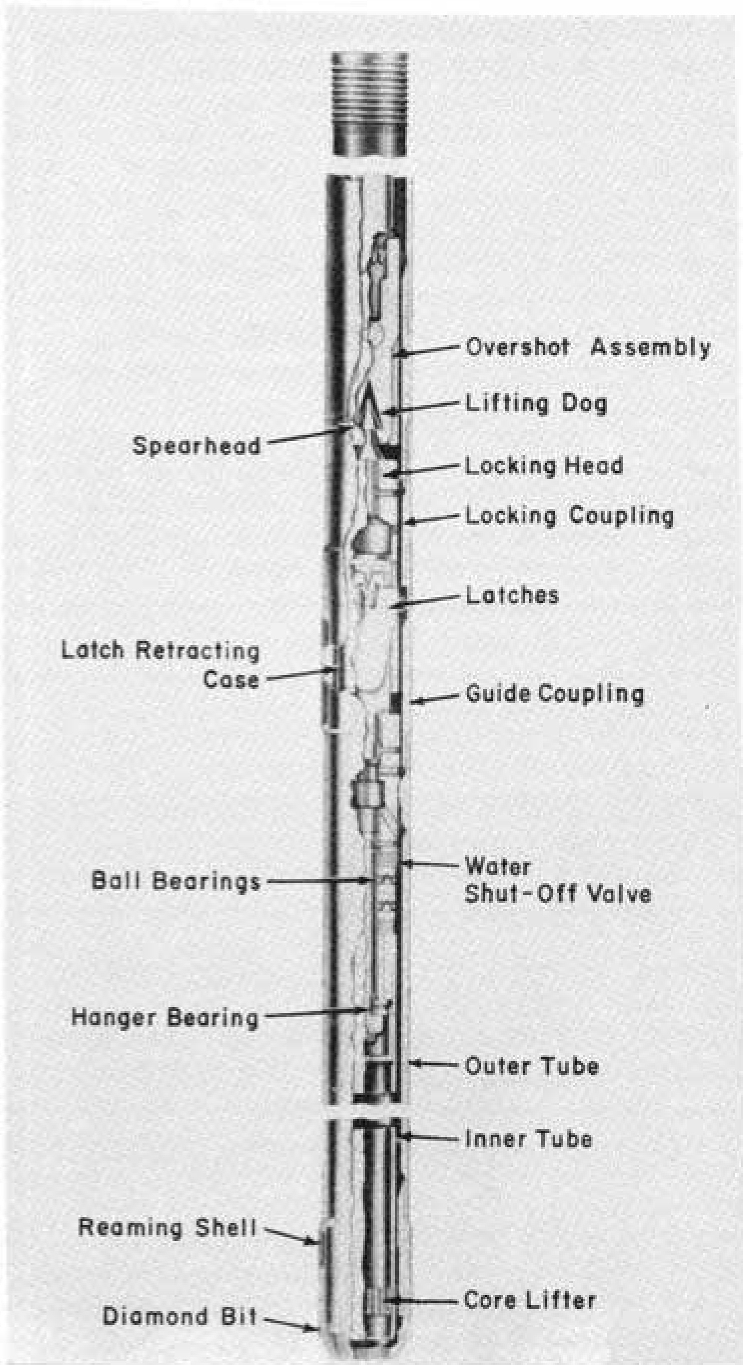
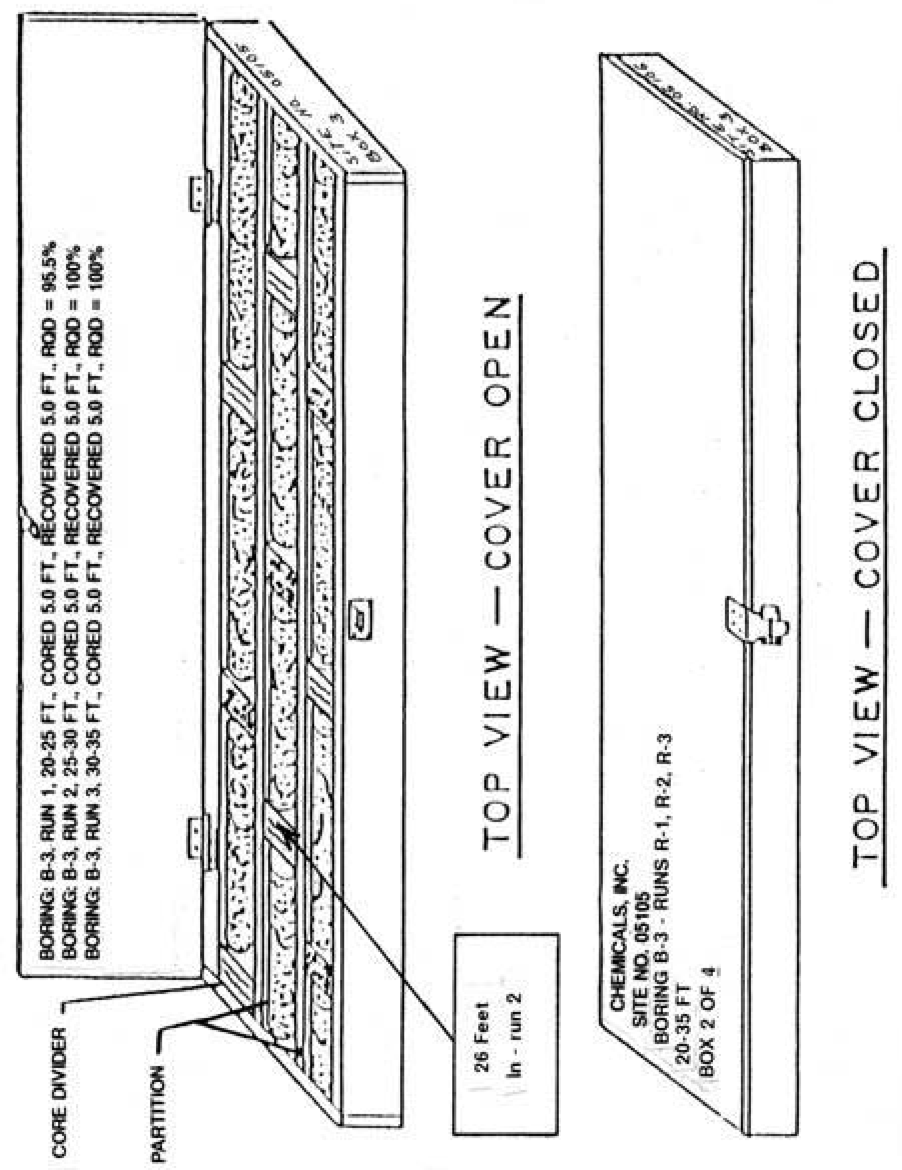


Figure 3.6-3

Source: Winterkorn et al. (1975)

Wireline Core Barrel.



After Winterkorn et al. (1975)

Figure 3.6-4

Core Box.

			Boring no:
Client			**Project no:**
Contractor		**Date started**	**Completed**
Method	**Casing size**	**PID**	**Protect'n level**
Ground el.	**Soil drilled**	**Rock drilled**	**∇ Below grnd**
Logged by	**Ch'd by**	**Date**	**Site**

Depth (ft)	PID ambient air	Sample no. and type[1]	Sample	Pen/Rec	CLP	GC	PID sample (ppm)	Soil/rock description	Lithologic symbol	Well data	Soil class	Blows/6-in. or RQD % (0 20 40 60 80 100)	Elevation (ft)

[1] U = Thin wall tube S = Split spoon R = Rock

Source: ABB-ES

Figure 3.6-5

Example No. 1 of Borehole Core Log.

VISUAL IDENTIFICATION ROCK CORES

SHEET_______ OF_______

JOB NO.	BY	DATE	CHK'D BY
BORING NO.	SAMPLE	CORE DIA. (IN.)	DEPTH (FT.)

CORE LENGTH (FT.)	CORE RECOVERY (FT.)	RQD	%	ROCK QUALITY

CORE RECOVERY (FT.)	0.3 FT. CORE RECOVERY	ROCK DESCRIPTION AND IDENTIFICATION

DEPTH (FT.)

1.0

2.0

3.0

4.0

5.0

TOTAL________ FT. TOTAL________ FT.

________ (%) ________ (%)

Source: ABB-ES

Figure 3.6-6

Example No. 2 of Borehole Core Log.

DCDMA standards	Core diam. (bit ID)		Hole diam. (reaming shell OD)	
Size	in	mm	in	mm
EWX and EWM	0.845	21.5	1.485	37.7
AWX and AWM	1.185	30.1	1.890	48.0
BWX and BWM	1.655	42.0	2.360	59.9
NWX and NWM	2.155	54.7	2.980	75.7
2 3/4 in, 3 7/8 in	2.690	68.3	3.875	98.4
4 in, 5 1/2 in	3.970	100.8	5.495	139.6
8 in, 7 3/4 in	5.970	151.6	7.755	196.8
Wireline Size				
AQ	1 1/16	27.0	1 57/64	48.0
BQ	1 7/16	36.5	2 23/64	60.0
NQ	1 7/8	47.6	2 63/64	75.8
HQ	2 1/2	63.5	3 25/32	96.0
PQ	3 11/32	85.0	4 53/64	122.6

Source: Hunt (1984)

Table 3.6-1

Standard Sizes of Diamond Core Bits and Wireline

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 3.7 ROCK CLASSIFICATION

SECTION 3.7
ROCK CLASSIFICATION

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3.7 ROCK CLASSIFICATION

3.7-1 PURPOSE

In hydrogeological and geotechnical studies, the purpose of rock classification is to identify the properties of the bedrock that influence site conditions, particularly such factors as water quality, ground water movement, and stability. Bedrock field investigations usually involve two parts: (1) description of the rock type(s) and associated textural characteristics, and (2) description of weathering and structural features of the bedrock. These properties affect the water-bearing and water transmission qualities of the bedrock. Field bedrock investigations may employ any or all of the following methods:

- Mapping bedrock exposures (outcrops) to determine rock type and condition; description of surface weathering and structural features.

- Subsurface investigations; logging of rock core or chips; geophysical logging of borehole.

- Installing bedrock monitoring wells to measure horizontal and vertical gradients, hydraulic conductivity, and water quality.

Descriptions used for the purpose of rock classification should employ, as much as possible, commonly accepted terms that will convey the same meaning to all who read them.

General reference material describing rock characteristics for classification purposes are contained in Appendix A. Examples of appropriate field logs are also included in Appendix A.

3.7-2 METHODOLOGY

A procedure for classifying and describing rocks in hand specimen or rock core is presented in the following paragraphs. The procedure has been divided into two parts: (1) determining the rock type and describing its associated petrologic properties, and (2) describing both large- and small-scale structural features.

3.7-2.1 Rock Type

Rocks are divided into three fundamental categories: igneous, sedimentary, and metamorphic. Categorization is based primarily on origin and secondarily on mineral content, grain size, and texture. Mineral content, grain size, and texture have a direct influence on the chemical and mechanical properties of a rock and, consequently, are important in hydrogeologic and engineering assessments. For example, many sedimentary sandstones have a primary permeability of 10^{-} to 10^{-} cm/sec due to the pore space between the grains that comprise the rock. In comparison, most intrusive igneous rocks are made up of interlocking mineral crystals, which in the absence of secondary fractures have a very low primary permeability range of 10^{-} to less than 10^{-} cm/sec. Proper identification of the basic rock type and associated properties is essential for accurate assessment of the hydrogeologic and engineering properties of the rock.

For a given rock sample, the following five rock properties will be described, and used to determine the basic rock type. The method and terminology for determining each petrologic property will be described in detail.

- o hardness
- o color
- o texture
- o grain size
- o mineral content

Examples of field notes, tables, and logs to aid in describing rock types are included as figures and tables at the end of this section.

3.7-2.1.1 Hardness

Hardness is a measure of a rock's resistance to scratching or abrasion. Hardness should be measured by scratching the rock with a knife or hitting it with a geologist's hammer. The following criteria can be used to determine the hardness characteristics of a rock:

- o Hard: can be scratched with knife or pick only with difficulty; hard blows of hammer required to detach hand specimen.

- o Moderately hard: can be scratched with knife or pick; gouges or grooves to 1/16-inch deep can be incised by hand blow of point of a geologist's pick; hand specimens can be detached by moderate blow.

- o Moderately soft: can be grooved or gouged 1/4-inch deep by firm pressure on knife or pick point; can be excavated in small chips to pieces about 1 inch maximum size by hard blows of the point of a geologist's pick.

- o Soft: can be gouged or grooved readily with knife or pick point; can be excavated in fragments from chips to several inches in size by moderate blows of a pick point; small, thin pieces can be broken by finger pressure.

3.7-2.1.2 Color

Color is an important rock property used to distinguish one rock type from another. When describing the color, use only common names (e.g., gray, brown, or green) or simple combinations of these (e.g., yellow-brown). Also, the degree of color (i.e., light versus dark) should be employed. If minerals of different colors are present in the rock, a combination of color terms can be used to describe the dominant colors (e.g., white and black). Color descriptions should apply only to fresh rock surfaces. If the color refers to a weathered specimen, this should be noted. If more detail is needed, use the Rock Color Charts of the Geological Society of America, which incorporate hue, value, and chroma numbers.

3.7-2.1.3 Grain Size

Determination of grain size is important in assigning a rock sample to the correct rock group. Grain-size descriptions for clastic sedimentary rocks differ from those for crystalline sedimentary rocks and igneous and metamorphic rocks. The criteria for each category are presented herein. A hand lens is helpful in determining grain size. The following scheme can be used to describe the grain size for various rock types.

(a) Igneous, Metamorphic, and Crystalline Sedimentary Rocks

For igneous, metamorphic, and crystalline sedimentary rocks, the following textural terms should be used:

- Aphanitic: particles too small to be seen with the naked eye.
- Fine-grained: particles barely seen with the naked eye (<1 mm).
- Medium-grained: Particles seen with the naked eye to 1/8 inch (1 to 5 mm).
- Coarse-grained: particles greater than 1/8 inch (>5 mm).

(b) Clastic Sedimentary Rocks

For clastic sedimentary rocks, the following textural terms should be used:

- boulder: greater than 256 mm (>10 inches)
- cobble: 256 to 64 mm (10 to 2.5 inches)
- pebble: 64 to 4 mm (2.5 to .16 inches)
- granule 4 to 2 mm (.16 to .08 inches)
- very coarse sand: 2 to 1 mm (<.08 inches)
- coarse sand: 1 to 1/2 mm
- medium sand: 1/2 to 1/4 mm
- fine sand: 1/4 to 1/8 mm
- very fine sand: 1/8 to 1/16 mm
- silt: 1/16 to 1/256 mm
- clay: less than 1/256 mm

Figure 3.7-1 may be used to aid in the determination of grain size.

3.7-2.1.4 Texture

The texture of a rock refers to the overall aspect imparted by the sizes, shapes, and arrangement of grains. Textures and small-scale structures are often easier to recognize than minerals, and are a fundamental basis for rock classification. Textural terminology is generally specific to each basic rock type. A simplified, but adequate, list of textural terminology and criteria follows.

a) Igneous Rocks.

- Aphanitic: crystalline grains too small to be seen without magnification.
- Phaneritic: small grains are visible without magnification.
- Porphyritic: large crystals embedded in a more finely crystalline ground mass.
- Glassy: having no definite mineral grains.
- Fragmental: composed of fragments of minerals or angular, broken fragments of rocks.

(b) Sedimentary: Clastic Category

These rocks are made up of fragments or grains transported to the site of deposition (e.g., sandstone.)

- Sorting: a measure of how closely the clastic grains in a sediment approach being one size; ranges from poorly sorted to well-sorted (see Figure 3.7-2 to determine the appropriate classification.) In soils this referred to as grading (Section 3.5-3.3)
- Angularity: degree of rounding of individual grains; ranges from very angular to well-rounded (see Figure 3.7-3 to determine classification.)
- Sphericity: the degree to which the shape of the grain approaches that of a sphere.
- Bedding (Layering): parallel-banded or streaked appearance.
- Lamination: thin, 1/8-inch or less, parallel layers or beds.

(c) Sedimentary: Crystalline Category

These rocks are produced by in-situ mineral growth.

- Oolitic: consisting of spherical grains, (oolites).

- Massive: rock constituents neither grouped in layers nor oriented in parallel position.

(d) Metamorphic

Metamorphic textures are presented in Figure 3.7-4.

- Foliation: A planar arrangement of textural or structural features imparting a tendency to split into layers similar to the way the mineral mica breaks.

- Slaty: a pervasive parallel directional structure in fine-grained metamorphic rocks that permits splitting into thin sheets. The main difference between this and foliation is the slaty texture is finer grained.

- Phyllitic: a foliation that exhibits a silky sheen due to the parallel orientation of micaceous minerals. This is due to minute platy crystals.
- Schistose: a foliation in schist or other coarse grained rock due to parallel or elongate alignment of grains visible without magnification.

- Gniessic: a foliation due to compositional banding and roughly parallel alignment of minerals. This texture exhibits a striped appearance.

3.7-2.1.5 Mineral Content

If possible, the primary minerals in the rock will be identified (e.g., quartz, feldspars, and mica) and percentages estimated. Figure 3.7-5 can be used to aid in estimating percentages. Primary minerals are listed, starting with least abundant and progressing to the most abundant. A common rock name can be substituted for mineral names (e.g., granite or dolomite).

3.7-2.1.6 Identifying Rock Type

Rock types are identified using the five descriptive criteria as a basis. (The estimated percentages presented in Figure 3.7-5 rely on the visual prominence of the properties of texture, grain size, and mineralogy.) A simplified rock classification flow chart based on mineralogy, grain size, and texture is shown in Figure 3.7-6. Classification diagrams for each rock category (i.e., igneous, metamorphic, and sedimentary) are presented in Figure 3.7-7.

A descriptive rock name should be assigned. The degree of complexity will be based on the need for detail and the field person's ability. Generally, a simple rock name is sufficient. Examples of typical rock names, ranging from simple to detailed, follow:

- light gray limestone
- moderately soft, light brown to black phyllite
- hard, light gray, porphyritic granite
- soft, reddish-brown, well-sorted, rounded, pebble-cobble conglomerate

If possible and desirable, the formation name can be assigned to the rock; for example, "soft light gray to brown, garnet-staurolite schist, BERWICK FM".

3.7-2.2 Description of Weathering and Structural Features

In addition to describing the lithology of a rock sample, note the typical weathering and structural characteristics. Generally, these characteristics are identified by the inspection of surface exposures of bedrock in the vicinity of the area of interest. If possible, use a compass and clinometer to determine the orientation of structural features (e.g., foliation, bedding, and joints). Generally, outcrops are located on a site map and corresponding descriptions are noted in a field book. An example of a field description and tables to aid in describing weathering and structural features of bedrock outcrops are included in Appendix B. General methods for describing the weathering condition of an outcrop and its structural features are presented in the following section.

3.7-2.2.1 Weathering

Weathering results from the natural alteration of rock by physical and chemical processes. These processes include action of air and water, biological activity, and mechanical alteration. Weathering characteristics are important in both hydrogeological and geotechnical investigations. For example, permeability tends to increase as a function of weathering, and ultimately decreases again as the rock deteriorates towards a clayey soil. To classify the materials and attributes of the weathered rock, it is necessary to distinguish differing degrees of weathering in a rock. A descriptive classification of weathering based on simple field tests follows:

- Fresh: rock looks fresh; crystals look bright; a few joints may show slight staining; rock rings under hammer, if crystalline.

- Slight: rock generally looks fresh; joints stained and discoloration extends into rock up to 1 inch; may show thin clay coatings, if open; open joints may contain clay; in granitoid rocks, some occasional feldspar crystals are dull and discolored; crystalline rocks ring under hammer blows.

- Moderate: significant portions of the rock show discoloration and weathering effects; in granitoid rocks, most feldspars are dull and discolored, some appear like clay; rock has dull sound under hammer blows and shows significant loss of strength compared to fresh rock.

- Moderately severe: all rock material except quartz minerals discolored or stained; in granitoid rocks, all feldspars dull and discolored and majority show kaolinization; rock shows severe loss of strength and can be excavated with geologist's pick; rock gives "clunk" sound when struck by hammer.

- Severe: all rock material except quartz minerals discolored or stained; rock "fabric" clear and evident but reduced in strength to strong soil; in granitoid rocks, all feldspars kaolinized to some extent; some fragments of strong rock usually remain.

- Complete: rock reduced to "soil"; rock "fabric" not discernible or discernible only in small scattered locations; quartz may be present as dikes or stringers (i.e., saprolite).

3.7-2.2.2 Structure

Structure refers to the general disposition, attitude, arrangement, or relative positions of a rock body or portion of a rock body. Structures represent a discontinuity or major heterogeneity in the rock body. The term "texture" is generally used for small-scale features affecting the minerals and particles in a rock, whereas "structure" generally refers to variations in the component parts of a rock body as a whole. Generally structural features are best observed in outcrops rather than hand specimens. Rock continuity descriptions specific to drill cores are presented at the end of this section. It is important that measurements of structural orientations be made on in-place rock, rather than boulders. If the nature of the outcrop (e.g., outcrop or erratic) is uncertain, it should be noted.

(a) Discontinuities

Discontinuities are surfaces representing breaks or fractures separating the rock mass into discrete units. Descriptive terminology and criteria for describing discontinuities follow.

(1) Types of Discontinuities. (For more detailed descriptive terms, see Appendix B).

- Fracture: break in a rock due to mechanical failure by stress. Includes cracks, joints, and faults.

- Crack: a partial or incomplete fracture.

- Joint: a set of simple fractures along which no shear displacement has occurred (usually occur with parallel joints to form part of a joint set.)

- Shear: a fracture along which differential movement has taken place parallel to the surface sufficient to produce slickensides, striations, or polishing; it may be accompanied by a zone of fractured rock up to a few inches wide.

- o Shear Zone: a band or zone of parallel, closely spaced fractures in rocks that are crushed or brecciated; it may range from less than a foot to many feet in width.

- o Fault: a fracture along which there has been obvious displacement. Faults may be accompanied by gouge, brecciation and/or mylonization.

(2) Spacing. Spacing refers to the perpendicular distance between discontinuities. The following items are recommended to describe fractures.

- o very close: spacing is less than 2 inches
- o close: spacing is 2 to 12 inches
- o moderately close: spacing is1 to 3 feet
- o wide: spacing is 3 to 10 feet
- o very wide: spacing is more than 10 feet

3) Tightness: Tightness describes the degree of closure of the opposing faces of the discontinuity.

- o Tight: discontinuity clearly visible; interlocking surfaces; may require force to separate.

- o Open: spaces clearly visible along discontinuity; opening may be filled with weathered material (i.e., clay); easily separated.

- o Healed: discontinuity visible; generally will not separate easily; most commonly rehealed with calcite and quartz.

(4) Attitude. Attitude is the spatial arrangement (i.e., strike and dip) for all sets of discontinuities. Descriptive terms for dip are as follows:

Description	Degrees of Dip
Horizontal	0 - 5°
Shallow or low angle	5 - 35°
Moderately dipping	35 - 55°
Steep or high angle	55 - 85°
Vertical	85 - 90°

(5) Regularity. Regularity is the levelness of the surface of the fracture.

- o Plane: The fractured rock surface is flat and uniform.
- o Smooth: The fracture is smooth to the touch; may appear polished and uniform in appearance.
- o Undulating: The surface is wavy.
- o Rough: The fractured surface is rough to the touch; hand does not slide easily along the surface.
- o Slickenside: The fracture surface exhibits parallel striations resulting from brittle movement; "ridged" surface, usually feels smooth in one direction and rough in the opposite direction.

(6) Consistency. Consistency is a determination of the uniformity of the discontinuities throughout the formation.

(7) Filling. Filling describes the nature and thickness of the material, if any, in the space between discontinuities. This filling may consist of weathered or altered rock, clayey material, etc.

(b) Vertical Spacing of Layering

The vertical spacing of layering or planar features within a rock should be described. Layering is a generic term and includes such planar features as bedding and foliation. It is used when the exact category is uncertain. Suggested terminology is as follows:

Descriptive Term	Spacing
very thin	less than 2 inches
thin	2 to 12 inches
medium	1 to 3 feet
thick	3 to 10 feet
very thick	greater than 10 feet

(c) Descriptions Specific to Rock Cores

(1) Rock Core Discontinuity Rock core discontinuity is any natural break in a rock whether or not it has undergone relative displacement. Where applicable, utilize the following terminology in describing rock continuity:

Terminology	Length of Drill Stem Pieces*
extremely fractured	less than 1 inch
moderately fractured	1 to 4 inches
slightly fractured	4 to 8 inches
sound	greater than 8 inches

* Length of drill stem pieces between natural fractures, not mechanical breaks due to the coring process

(2) Rock Quality Determination (RQD) The RQD (Deere, 1964) method of determining rock quality described in Section 3.6-3.4.3 is repeated here for convenience:

Sum the total lengths of core fragments, counting only those pieces of core that are 4 inches (10 cm) in length or longer (as measured along the vertical axis) and are hard and sound. If the core is broken by handling or by the drilling process, the fresh broken pieces are fitted together and counted as one piece, provided they form the requisite length of 4 inches (10 cm).

The RQD is represented as a percentage. The percentage is derived by dividing the total sum of core pieces (4 inches or greater) by length of the run minus the length of the core left in the hole times 100.

$$RQD = \frac{\sum L(<4)}{(R-C)} \times 100$$

Where: $\sum L(<4)$ = Sum of total length pf core pieces 4 inches or greater
R = Length of total core run
C = Length of core left in borehole

RELATION OF RQD AND ROCK QUALITY

RQD (%)	Description of Rock Quality
0 to 25	very poor
25 to 50	poor
50 to 75	fair
75 to 90	good
90 to 100	excellent

Note: RQD can only be used on NQ core (1-7/8 inch) or larger. The RQD should always be shown on the core log as a percentage.

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SECTION 3.7
ROCK CLASSIFICATION

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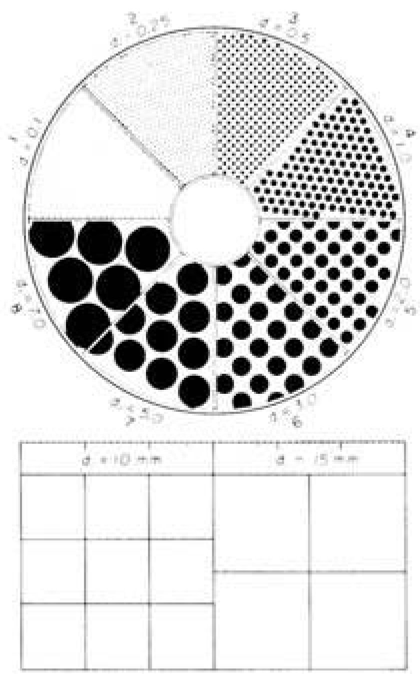
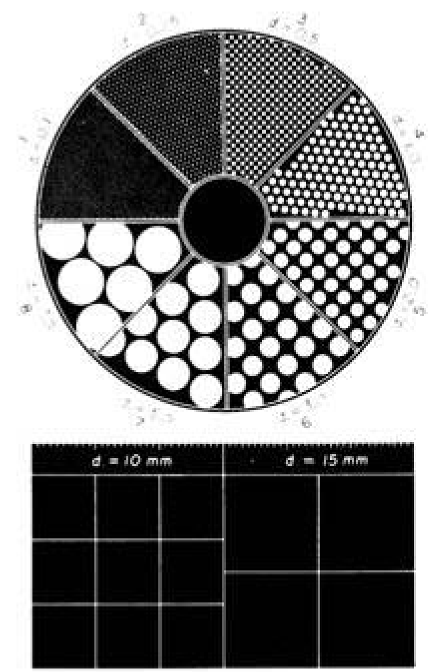
DARK PARTICLES



LIGHT PARTICLES



Place sand grains or rock particles in the central part of the circle. Compare the size of the particles with those on the graph with the aid of a magnifying glass. Record the corresponding number (1,2,3,4,5,6,7,8) in notebook. For samples with particles of varying sizes, record the most common size first.

Source: AGI Data Sheets (1982)

Figure 3.7-1

Charts for Determining the Size of Sedimentary Rock Particles.

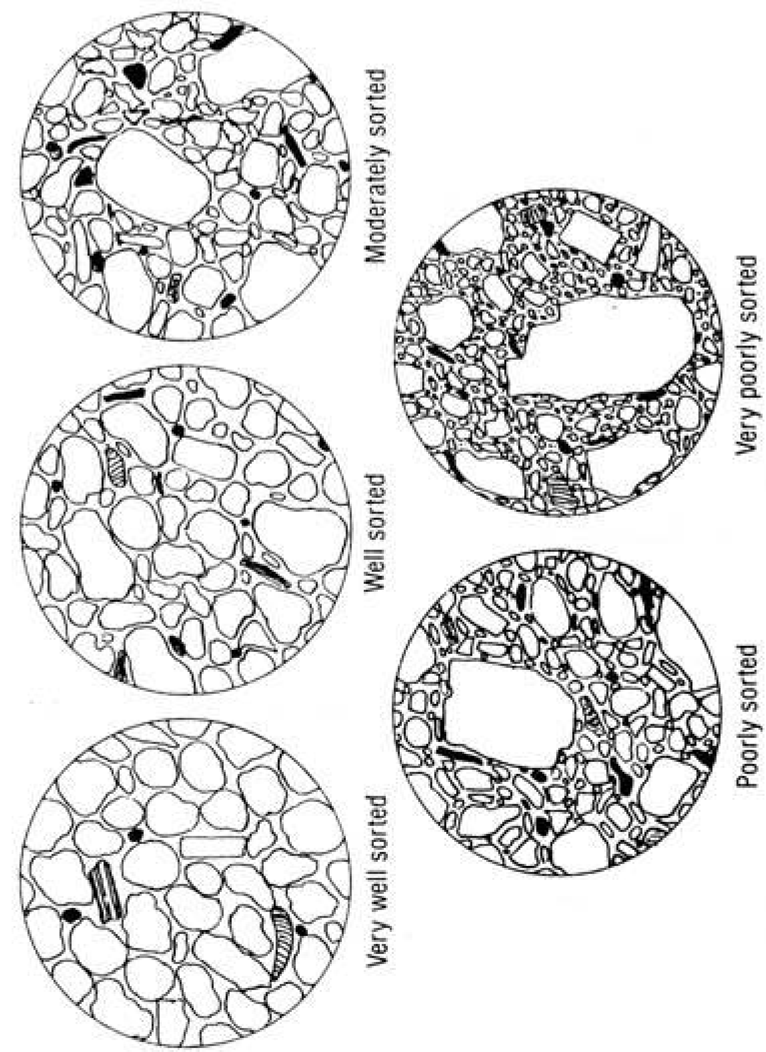
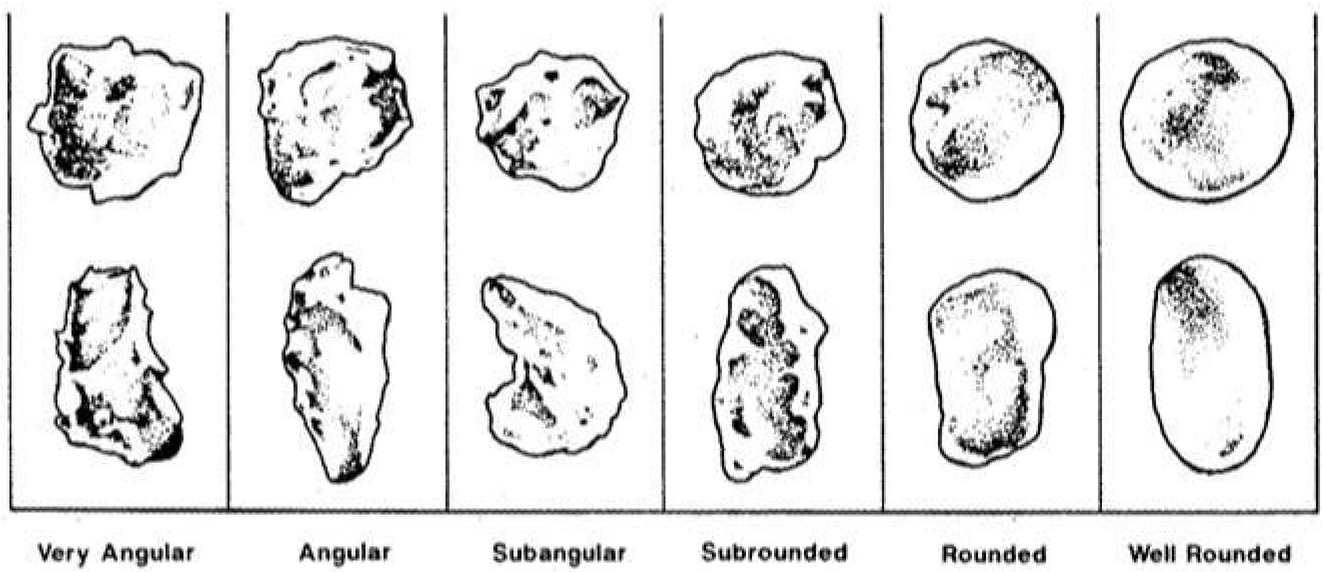


Figure 3.7-2

Classification Aid for Evaluating Degree of Sorting of Clastic Materials in Rocks.

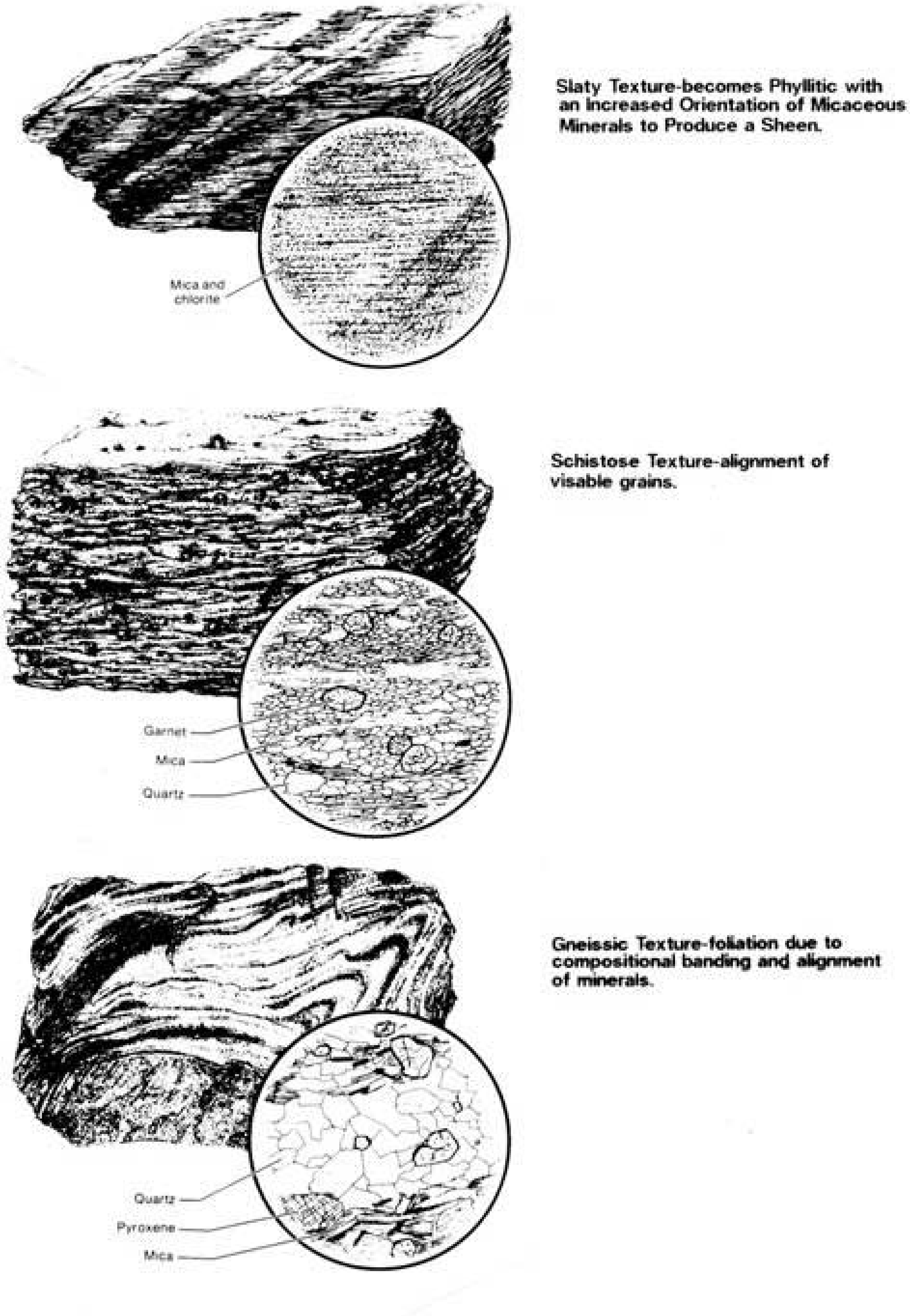
Source: Compton (1985)



Source: Compton (1985) after Powers (1953)

Figure 3.7-3

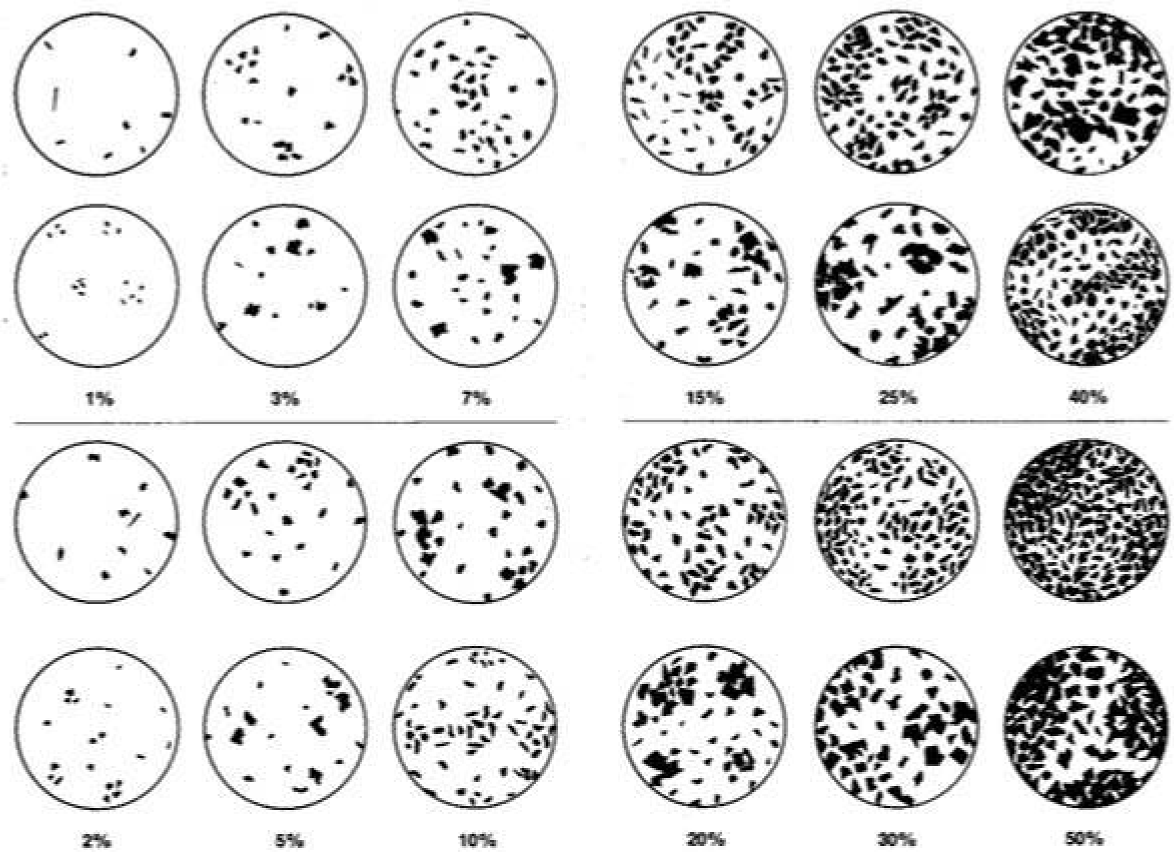
Classification Aid for Determining the Degree of Angularity of Particles in Rocks.



Source: Hamblin (1975)

Figure 3.7-4

Metamorphic Textures.



Source: AGI Data Sheet (1982)

Figure 3.7-5

Comparison Chart for
Estimating Percentage Composition.

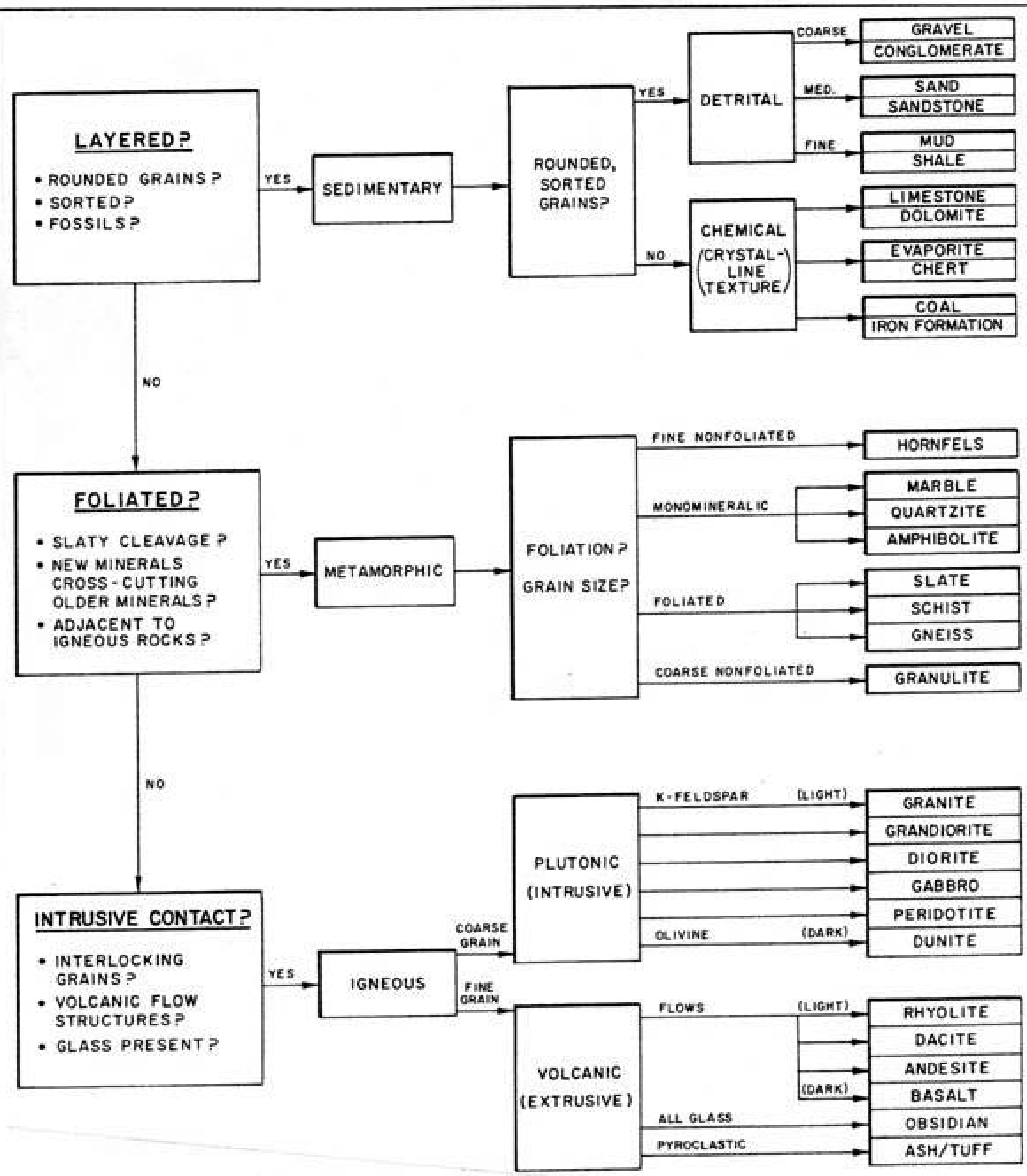


Figure 3.7-6

Rock Identification Flow Chart.

Source: After Press and Siever (1982)

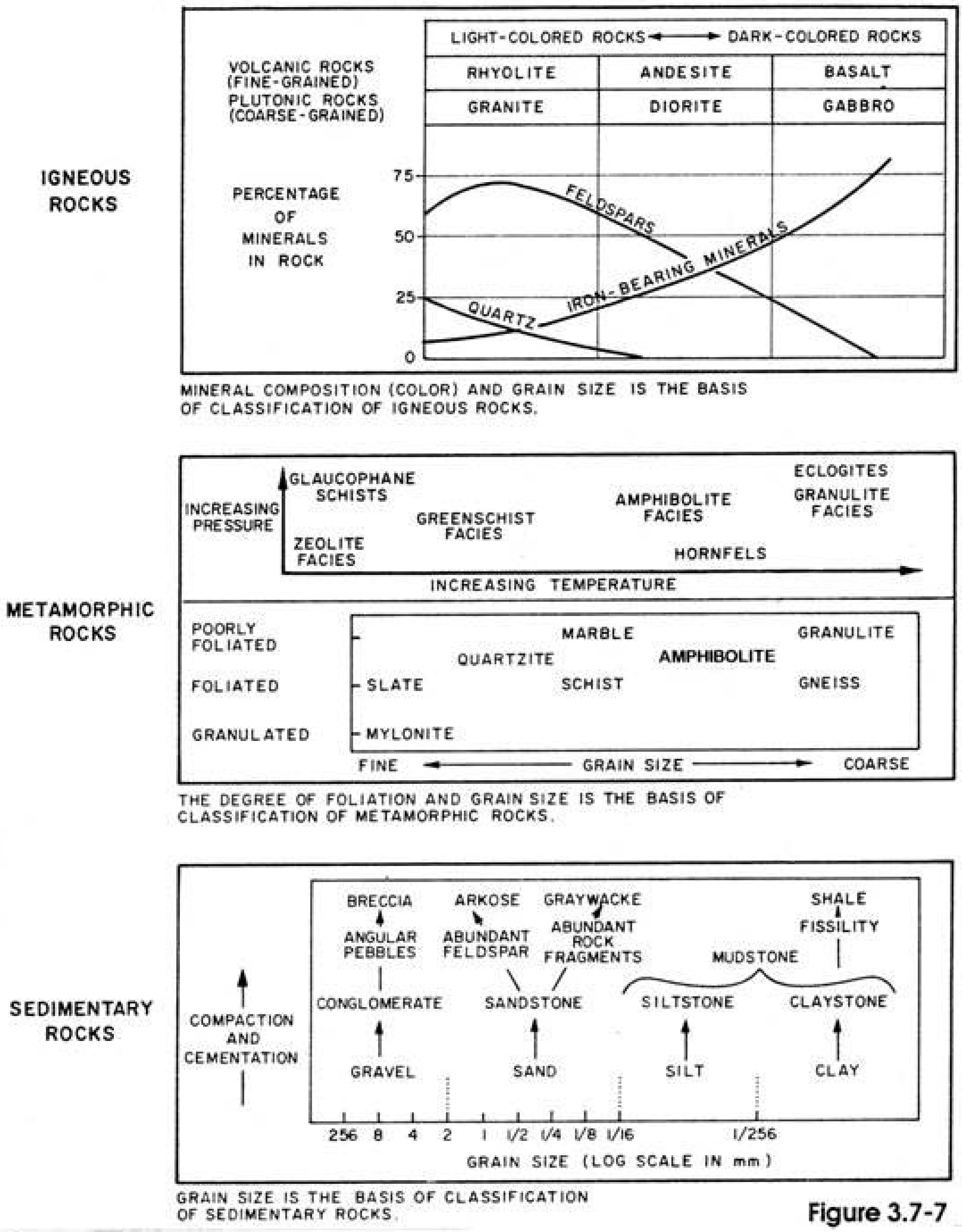


Figure 3.7-7

Source: After Press & Siever

Classification Schemes for Igneous, Metamorphic and Sedimentary Rocks.

APPENDIX A

EXAMPLES OF FIELD PROCEDURES, TABLES, AND LOGS FOR ROCK DESCRIPTIONS

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Characteristic	Description of grade or class
INTACT ROCK	
Hardness	Class I–V, extremely hard to very soft.
Weathering grade	F, WS, WM, WC, RS, fresh to residual soil.
Rock type	Identify type, minerals, and cementing agent.
Coloring	Red, gray, variegated, etc.
Texture (gradation)	Coarse, medium, fine, very fine.
Fabric: Form	Equigranular, porphyritic, amorphous, platy, (schistose or foliate), isotropic, anisotropic.
Orientation	Horizontal, vertical, dipping (give degrees).
DISCONTINUTIES	
Joint spacing	Very wide, wide, moderately close, close, very close. Give orientations of major joint sets. Solid, massive, blocky, fractured, crushed mass.
Joint conditions Form	Stepped, smooth, undulating, planar.
Surface	Rough, smooth, slickensided.
Openings	Closed, open (give width).
Fillings	None, sand, clay, breccia, other minerals.
Other discon-tinuities and mass characteristics	Faults, slickensides, foliation shear zones, cleavage, bedding, cavities, and groundwater conditions. Included in overall mass description.

NOTE: Example as applied to a geologic unit: "Hard, moderately weathered GNEISS, light gray, medium grained (quartz, feldspar, and mica); strongly foliated (anisotropic), joints moderately spaced (blocky), planar, rough, open (to 1 cm), clay filled."

Source: Hunt (1984)

Figure A-1

Field Description of Rock Masses.

Major classes	Subdivisions of major classes based on mineral composition							
Minerals†	Light-colored rocks				Medium-colored		Dark-colored rocks	
	Orthoclase feldspar		Ortho- or Plagio-clase feldspar		Plagioclase		Plagio-clase	No feld-spar
	BHP		BHP		BHP	HBP	PHOA	OPHBA
Grain size	With Q	Without Q	With Q	Without Q	With Q	Without Q	Without Q	No Q
Coarse > 1 mm	Pegmatite Granite							
Phanerites Equigranular > 1 mm	Granite	Syenite	Grano-diorite	Monzonite	Tonalite (quartz diorite)	Diorite	Gabbro	Peridotite Pyroxenite Dunite (O)
Micro-phanerites Equigranular < 1 mm	Aplite	Micro-syenite	Micro-grano-diorite	Micro-monzomite	Micro-tonalite	Micro-diorite	Dolerite (diabase)	
Porphyries	All phanerites are found with phenocrysts (granite porphyry, etc.)							
Aphanites and aphanite porphyries	Rhyolite	Trachyte	Quartz, latite	Latite	Dacite	Andesite	Basalt	
	Felsite (and felsophyre)							
Classes	Obsidian and pitchstone							
Porous	Pumice				Scoria		Vesicular basalt	

Legend: Plutonic rocks – Volcanic rocks – Border rocks –

† Minerals: A = augite, B = biotite, H = hornblende, P = pyroxene,
O = olivine, Q = quartz.

*After Pirsson and Knopf (1955).[3] (Excludes pyroclastic rocks.) Adapted with permission of John Wiley & Sons, Inc.

Source: Hunt (1984)

Figure A-2

Classification of Igneous Rocks.

Rock	Characteristics
	FINE-GRAINED—RAPID COOLING
Andesite	Generally dark gray, green, or red. Pure andesite is relatively rare, and it is usually found with phenocrysts. Porphyritic andesite and basalt compose about 95% of all volcanic materials.
Basalt	Most abundant extrusive rock; found in all parts of the world and beneath the oceans. Colors range from grayish to greenish black to black. Fine-grained with a dense compact structure. Often contains numerous voids (vesicular basalt).
Rhyolite	The microcrystalline equivalent of granite formed at or near the surface. Characteristically white, gray, or pink and nearly always contains a few phenocrysts of quartz or feldspar.
Felsite	Occurs as dikes, sills, and lava flows. The term felsite is used to define the finely crystalline varieties of quartz-porphyries or other light-colored porphyries that have few or no phenocrysts and give but slight indications to the unaided eye of their actual mineral composition.
	GLASSY ROCKS—VERY RAPID CHILLING
Obsidian	Solid natural glass devoid of all crystalline grains, generally black with a brilliant luster and a remarkable conchoidal fracture.
Pitchstone	A variety of obsidian with a resinous luster.
Pumice	Extremely vesicular glass; a glass froth.
Scoriae	Formations that have as much void space as solids.

Rock	Characteristics
	COARSE TO MEDIUM GRAINED—VERY SLOW TO SLOW COOLING
Pegmatite	Abundant as dikes in granite masses and other large bodies. Chiefly quartz and feldspar appearing separately as large grains ranging from a centimeter to as large as a meter in diameter.
Granite	The most common and widely occurring igneous rock. Fabric roughly equigranular normally. Light colors contain chiefly quartz and feldspar; gray shades contain biotite mica or hornblende.
Syenite	Light-colored rock differing from granite in that it contains no quartz, consisting almost entirely of feldspar but often containing some hornblende, biotite, and pyroxine.
Diorite	Gray to dark gray or greenish, composed of plagioclase feldspar and one or more of the ferromagnesian minerals. Equigranular fabric.
Gabbro	Dark-colored rock composed chiefly of ferromagnesian minerals and plagioclase feldspar.
Peridotite	Dark-colored rocks composed almost solely of ferromagnesian minerals. Olivine predominant; negligible feldspar. Hornblende or pyroxenes associated. Readily altered.
Pyroxenite	As above but pyroxene alone or predominant.
Hornblendite	As above but hornblende alone or predominant.
Dunite	Major constituent is olivine, which alters readily to serpentine.
Dolerite (or diabase)	Dark-colored rock intermediate in grain size between gabbro and basalt. Abundant as thick lava flows that have cooled slowly.

Figure A-3

Source: Hunt (1984)

Characteristics of Some Igneous Rocks.

Rock type	Material*	Diameter, mm	Composition	Depositional environment
			DETRITAL	
Conglomerate	Boulders	>256	Same as source rock.	Along stream bottoms. Seldom found in rock masses.
	Cobbles	256–64	Same as source rock.	Along stream bottoms. Deposited as alluvial fans and in river channels.
	Pebbles	64–4	As for cobbles or sand.	As for cobbles; also deposited in beaches.
	Granule	4–2	As for cobbles or sand.	As for pebbles and sand.
Sandstone	Sand	2–0.02	Primarily quartz; also feldspar, garnet, magnetite. Some locales: hornblende, pyroxene, shell fragments.	All alluvial deposits: stream channels, fans, floodplains, beaches, deltas. Occasionally aeolian.
Siltstone	Silt	0.02–0.002	As for sand; often some clay particles.	Deltas and floodplains.
Shales	Clay	<0.002	Colloidal sizes of the end result of decomposition of unstable minerals yielding complex hydrous silicates (see Art. 5.3.3).	Quiet water. Salt water: Clay particles curdle into lumps and settle quickly to the bottom. Show no graded beds. Freshwater: Settle slowly; are laminated and well-stratified, showing graded bedding.
			NONDETRITAL	
Limestone	Calcareous precipitate		Massive calcite ($CaCO_3$).	Deep, quiet water.
Coquina	Calcareous precipitates		Cemented shells.	Along beaches, warm water.
Chalk	Calcareous precipitates		Microscopic remains of organisms.	Clear, warm, shallow seas.
Dolomite	Calcareous precipitates		Dolomite—$CaMg(CO_3)_2$.	Seawater precipitation or alteration of limestone.
Gypsum†	Calcareous precipitates		Gypsum—$CaSO_4 \cdot 2H_2O$.	Saline water.
			DETRITAL	
Anhydrite†	Calcareous precipitate		Anhydrite—$CaSO_4$.	Saline water.
Halite†	Saline precipitates		Sodium chloride.	Saline water.
Coal	Organic		Carbonaceous matter.	Swamps and marshes.
Chert	Silicate		Silica, opal.	Precipitation.

*The Wentworth scale.
†Evaporites.

*The Wentworth scale.
†Evaporites.

Source: Hunt (1984)

Figure A-4

Broad Classification of Sedimentary Rocks.

Rock	Characteristics
Metaconglomerate	Heat and pressure cause the pebbles in a conglomerate to stretch, deform, and fuse.
Quartzite	Results from sandstone so firmly fused that fracture occurs across the grains, which are often imperceptible.
Marble	Results from metamorphism of limestone or dolomite and is found with large and small crystals, and in many colors including white, black, green, and red. Metamorphosed limestone does not normally develop cavities. Very hard.
Serpentinite	Derived from serpentine. Generally compact, dull to waxy luster, smooth to splintery fracture, generally green in color and often soft unless it contains significant amounts of quartz. Can have foliate fabric.
Soapstone	Derived from talc; generally gray to green color, very soft and easily trimmed into shapes with a knife, without cleavage or grain, and resists well the action of heat or acids.
Hornfels	Rocks baked by contact metamorphism into hard aphanitic material, with conchoidal fracture, dark gray to black color, often resembling a basalt.
	OTHER FORMS
Migmatite	Signifies a rock that is a complex intermixture of metamorphic and granular igneous rocks such as formed by the injection of granite magma into foliated rocks.
Mylonites	Produced by intense mechanical metamorphism; can show strong lamination but the original mineral constituents and fabric have been crushed and pulverized by the physical processes rather than altered chemically. Common along the base of overthrust sheets and can range from very thin, to a meter or so, to several hundreds of meters thick. Shale mylonites form very unstable conditions when encountered in cut slopes or tunneling. They are formed by differential movement between beds.

Source: Hunt (1984)

Figure A-5

Characteristics of Metamorphic Rocks with Massive Fabric and Other Forms.

Rock	Characteristics
Gneiss	Coarse-grained; imperfect foliation resulting from banding of different minerals. The foliation causes lenticular planes of weakness resulting in slabbing in excavations. Chief minerals are quartz and feldspar, but various percentages of other minerals (mica, amphibole, and other ferromagnesians) are common. The identification of gneiss includes its dominant *accessory* mineral such as hornblende gneiss biotite gneiss or general composition, i.e., granite gneiss
Paragneiss	Derived from sedimentary rocks
Orthogneiss	Derived from feldspathic igneous rocks
Schist	Fine-grained, well-developed foliation, resulting from the parallel arrangement of platy minerals (termed *schistosity*). The important platy minerals are muscovite, chlorite, and talc. Schist is identified by the primary mineral as mica schist chlorite schist, etc. Garnet is a common accessory mineral to mica schist and represents intense metamorphism. Schists and gneisses commonly grade into each other and a clear distinction between them is often not possible.
Amphibolite	Consist largely of amphibole and show more or less schistose form of foliation. Composed of darker minerals and, in addition to hornblende, can contain quartz, plagioclase feldspar, and mica. They are hard and have densities ranging from 3.0 to 3.4. Association with gneisses and schists is common in which they form layers and masses that are often more resistant to erosion than the surrounding rocks.
Phyllite	Soft, with a satinlike luster and extremely fine schistosity. Composed chiefly of chlorite. Very unstable in cut slopes. Grades to schists as the coarseness increases
Slate	Extremely fine-grained, exhibiting remarkable planar cleavage. Generally hard plates split from formations; once used for roofing materials.

Figure A-6

Source: Hunt (1984)

Characteristics of Some Metamorphic Rocks With Foliate Fabric.

Texture	Fabric: Foliated	Fabric: Massive
Coarse	Gneiss Amphibolite	Metaconglomerate Granite gneiss (imperfect foliations)
Medium	Schist (mica, chlorite, etc.)	Quartzite Marble Serpentinite Soapstone
Fine to microscopic	Phyllite Slate	Hornfels
Other forms	Migmatite: Complex composite rocks; intermixtures of metamorphic and igneous rocks.	
	Mylonites: Formed by intense mechanical metamorphism; show strong laminations, but original mineral constituents and fabric crushed and pulverized. Formed by differential shearing movement between beds.	

Source: Hunt (1984)

Figure A-7

Classification of Common Metamorphic Rocks.

Parent rock	Metamorphic derivative
SEDIMENTARY ROCKS	
Conglomerate	Gneiss, various schists, metaconglomerate
Sandstone	Quartzite, various schists†
Shale	Slate, phyllite, various schists
Limestone	Marble†
IGNEOUS ROCKS	
Coarse-grained feldspathic, such as granite	Gneiss, schists, phyllites
Fine-grained feldspathic, such as felsite and tuff	Schists and phyllites
Ferromagnesian, such as dolerite and basalt	Hornblende schists, amphibolite
Ultramafic, such as peridotite and pyroxene	Serpentine and talc schist

*After Pirsson and Knopf (1955).[3] Reprinted with permission of John Wiley & Sons, Inc.

†Depends on impurities.

Source: Hunt (1984)

Figure A-8

Metamophic Derivatives of Igneous and Sedimentary Rocks.

FIELD HARDNESS: A measure of resistance to scratching or abrasion.

- **Very hard** - Cannot be scratched with knife or sharp pick. Breaking of hand specimens requires several hard blows of geologist's pick.
- **Hard** - Can be scratched with knife or pick only with difficulty. Hard blow of hammer required to detach hand specimen.
- **Moderately hard** - Can be scratched with knife or pick. Gouges or grooves to 1/4 in. deep can be excavated by hard blow of point of a geologits's pick. Hand specimens can be detached by moderate blow.
- **Medium** - Can be grooved or gouged 1/16 in. deep by firm pressure on knife or pick point. Can be excavated in small chips to pieces about 1 in. maximum size by hard blows of the point of a geologist's pick.
- **Soft** - Can be gouged or grooved readily with knife or pick point. Can be excavated in chips to pieces several inches in size by moderate blows of a pick point. Small thin pieces can be broken by finger pressure.
- **Very soft** - Can be carved with knife. Can be excavated readily with point of pick. Pieces 1 in. or more in thickness can be broken with finger pressure. Can be scratched readily by fingernail.

WEATHERING: The action of the elements in altering the color, texture and composition of the rock.

- **Fresh** - Rock fresh, crystals bright, few joints may show slight staining. Rock rings under hammer if crystalline.
- **Very slight** - Rock generally fresh, joints stained, some joints may show thin clay coatings, crystals in broken face show bright. Rock rings under hammer if crystalline.
- **Slight** - Rock generally fresh, joints stained, and discoloration extends into rock up to 1 in. Joints may contain clay. In granitoid rocks some occasional feldspar crystals are dull and discolored. Crystalline rocks ring under hammer.
- **Moderate** - Significant portions of rock show discoloration and weathering effects. In granitoid rocks, most feldspars are dull and discolored; some show clayey. Rock has dull sound under hammer and shows significant loss of strength as compared with fresh rock.
- **Moderately severe** - All rock except quartz discolored or stained. In granitoid rocks, all feldspars dull and discolored and majority show kaolinization. Rock shows severe loss of strength and can be excavated with geologist's pick. Rock goes "clunk" when struck.
- **Severe** - All rock except quartz discolored or stained. Rock "fabric" clear and evident, but reduced in strength to strong soil. In granitoid rocks, all feldspars kaolinized to some extent. Some fragments of strong rock usually left.
- **Very severe** - All rock except quartz discolored or stained. Rock "fabric" discernible, but mass effectively reduced to "soil" with only fragments of strong rock remaining.
- **Complete** - Rock reduced to "soil". Rock "fabric" not discernible or discernible only in small scattered locations. Quartz may be present as dikes or stringers.

ROCK CONTINUITY: Any break in a rock whether or not it has undergone relative displacement.

- Extremely Fractured - Drill core stem less than 1 in.
- Moderately Fractured - Drill core stem 1in. to 4 in.
- Slightly Fractured - Drill core stem 4 in. to 8 in.
- Sound - Drill core stem greater than 8 in.

TEXTURE: Terminilogy used to identify size, shape and arrangement of constituent elements.

- Amorphous - Too small to be seen with naked eye.
- Fine Grained - Barely seen with naked eye.
- Medium Grained - Barely seen with naked eye to 1/8 in
- Coarse Grained - 1/8 in. to 1/4 in.
- Very Coarse Grained > 1/4 in.

DISCONTINUITIES: Surfaces representing breaks or fractures separating the rock mass into discrete units.

- **Crack** - A partial or incomplete fracture
- **Joint** - A simple fracture along which no shear displacement has occurred. May form joint sets.
- **Shear** - A fracture along which differential movement has taken place parallel to the surface sufficient to produce slickensides, striations or polishing. May be accompanied by a zone of fractured rock up to a few inches wide.
- **Fault** - A major fracture along which there has been appreciable displacement and accompanied by gouge and/or a severely fractured adjacent zone.
- **Shear or Fault Zone** - A band or zone of parallel, closely spaced shears or faults.

FRACTURES, BEDDING AND FOLIATION, SPACING AND ATTITUDE

Fractures	Bedding and Foliation	Spacing [1]	Attitude	Angle
Very close	Very thin	Less than 2 in.	Horizontal	0° - 5°
Close	Thin	2 in. - 1 ft.	Shallow or low angle	5° - 35°
Moderatley close	Medium	1 ft. - 3 ft.	Moderately dipping	35° - 55°
Wide	Thick	3 ft. - 10 ft.	Steep or high angle	55° - 85°
Very wide	Very thick	More than 10 ft.	Vertical	85° - 90°

Rock Quality Designation (RQD)

RQD in % = [Length of Core in Pieces 4 in. and Longer/Length of Run] x 100

Additional characteristics to further identify and evaluate the rock include: Type, Color, Cavities and Voids, Secondary Mineralization, Fossils, Swelling and Slaking Properties, etc.
Visual - manual rock descriptions consist of the following factors in the order presented. Example: Hard, slightly weathered, moderately fractured, gray, coarse grained CAMBRIDGE ARGILLITE, moderately close, tight, shallow dipping, smooth joints; minor shear parallel to bedding at 40 ft.; very thin, horizontal bedding; with siltstone partings and calcite fillings.
NOTE: 1. Spacing - Refers to perpendicular distance between discontunities.

Source: Haley and Aldrich (1977)

Figure A-9

Example of Visual-manual Identification of Rock Guide.

			Boring no:
Client			**Project no:**
Contractor		**Date started**	**Completed**
Method	**Casing size**	**PID**	**Protect'n level**
Ground el.	**Soil drilled**	**Rock drilled**	▽ **Below grnd**
Logged by	**Ch'd by**	**Date**	**Site**

Depth (ft)	PID ambient air	Sample no. and type[1]	Sample	Pen/Rec	CLP	GC	PID sample (ppm)	Soil/rock description	Lithologic symbol	Well data	Soil class	Blows/6-in. or RQD % 0 20 40 60 80 100	Elevation (ft)

[1] U = Thin wall tube S = Split spoon R = Rock

Source: ABB-ES

Figure A-10

Example of Field Boring Log for Rock.

DEFINITIONS	1. RQD (Rock Quality Designation)- The RQD is equal to the ratio of the cumulative length of pieces of sound core 4 inches or longer to the total length of the core run. If the core is broken by handling or by the drilling process (i.e., the fracture surfaces are fresh irregular breaks rather than natural joint surfaces), the fresh broken pieces are fitted together and counted as one piece provided that they form the requisite length of 4 inches. 2. Recovery - total length of core recovered as compared with the total length of the run.
DESCRIPTION OF INTACT ROCK	1. Structure or texture a) Grain size b) Stratified or bedded 1) Dip and strike 2) Thickness - laminated - less than 1 inch thin - 0 to 0.5 foot (bed thickness) medium - 0.5 to 1.0 feet thick - 1.0 to 3.0 feet very thick - more than 3.0 feet c) Massive - without stratification, foliation, banding, schistosity, etc. d) Foliated - (metamorphic rocks) 1) Highly (very schistose) 2) Moderately 3) Slightly e) Microfolding or contorting f) Banding - banded color changes g) Lineation 2. Voids - cavities, vesicles, pitting, fissures 3. Degree of weathering a) Extreme - Weathered to a soil. b) Severe - Most of sample weathered to, or almost to, a soil. c) Moderate - Rock is discolored. Some of the minerals have been decomposed and softened so that the soundness of the rock has been affected. Core samples can be abraded under finger pressure on some surface edges. d) Slight - Some discoloration and mineral decomposition. e) Minor - Little evidence of weathering but rock is essentially sound. f) Sound or fresh - Has no discoloration, is fresh in appearance. g) Seamed - Weathering has occurred along joints and fractures within unaltered rock mass.
DESCRIPTION OF ROCK DEFECTS	1. Joints a) Spacing 1) Very close - less than 2 inches 2) Close - 2 inches to 1 foot 3) Moderately close - 1 foot to 3 feet 4) Wide - 3 feet to 10 feet 5) Very wide - greater than 10 feet b) Open or closed c) Dip and strike 2. Fractures and faults - dip and strike, slickensides, striations 3. Breaks due to drilling, or discing due to stress relief 4. Infillings - products of weathering, mineralization, discoloration, etc.

Source: Haley and Aldrich, Inc.

Figure A-11

Example of Identification Rock Structure Guide.

VISUAL IDENTIFICATION ROCK CORES

SHEET_______OF_______

JOB NO.	BY	DATE	CHK'D BY	
BORING NO.	SAMPLE	CORE DIA. (IN.)	DEPTH (FT.)	
CORE LENGTH (FT.)	CORE RECOVERY (FT.)	RQD	%	ROCK QUALITY

CORE RECOVERY (FT.) | 0.3 FT. CORE RECOVERY | ROCK DESCRIPTION AND IDENTIFICATION

DEPTH (FT.)

1.0

2.0

3.0

4.0

5.0

TOTAL_________FT. TOTAL_________FT.

_________(%) _________(%)

Source: ABB-ES

Figure A-12

Example of Field Log of Rock Core.

APPENDIX B

EXAMPLES OF FIELD PROCEDURES AND TABLES TO AID IN DESCRIBING STRUCTURAL ROCK FEATURES

LIST OF FIGURES
APPENDIX B

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PROJECT ____ GEOLOGIST ____ DATE ____ FILE NO. ____

BORING NO. ____ RUN NO. ____ DEPTH from ____ to ____ RECOVERY ____ ft. ____ %

RQD ____ ft. ____ % (for entire run) AVERAGE DRILLING RATE ____ (min./ft.)

per foot basis beginning with ____ to ____ ft. (optional)

1 ____ % 2 ____ % 3 ____ % 4 ____ % 5 ____ %

6 ____ % 7 ____ % 8 ____ % 9 ____ % 10 ____ %

NO. OF PIECES ____ NO. OF CHIPS ____ NO. OF SOIL/CLAY LAYERS ____

Size and distribution of pieces in inches SCHMIDT HARDNESS ____

ROCK TYPE ____

MINERALS ____

FORMATION ____

REMARKS ____

$$RQD = \frac{\text{Summation of} \geq \text{NX core lengths} \geq 4"}{\text{Length of core run}}$$

1. Compute RQD only on rock core which has been moderately weathered or less
2. RQD adjustments required Yes ____ No ____

SAMPLES REMOVED FOR TESTING: None ____ (Depth, lengths) ____

CORE PHOTOGRAPHED ____ WATER LOSS ____

FIELD HARDNESS (Check one)

Very hard ____ Hard ____ Mod. Hard ____ Medium ____ Soft ____ Very Soft ____

WEATHERING (Check one)

Fresh ____ Very Slight ____ Slight ____ Moderate ____

Moderately Severe ____ Severe ____ Very Severe ____ Complete ____

ROCK CORE FRACTURES (CONTINUITY) (Check applicable and indicate depth)

Very Severe ____ Severe ____ Moderate ____ Slight ____ Very Slight ____

TEXTURE (Check one) COLOR

Amorphous (micro) ____ Fine gr. (macro) ____ Med. gr. ($<\frac{1}{8}"$) ____ Coarse gr. ($\frac{1}{8}" - \frac{1}{4}"$) ____ V. Coarse gr. ($>\frac{1}{4}"$) ____

DISCONTINUITIES (Indicate No.(s) of each type)

Crack ____ Joint ____ Shear ____ Fault ____ Shear or Fault Zones ____

Attitude: Hor. (0°-5°) ____ Shallow (5°-35°) ____ Mod. (35°-55°) ____ Steep (55°-85°) ____ Vert. (85°-90°) ____

Primary ____ Secondary ____ Other ____ (Indicate attitude by corresponding number)

Tightness: Tight ____ Open ____

Surfaces: Altered ____ Unaltered ____

Spacing: V. Close ____ Close ____ Mod. Close ____ Wide ____ V. Wide ____

Degree of Planeness: Plane ____ Curved ____ Irregular ____

Degree of Smoothness: Slick ____ Smooth ____ Rough ____

Fill between Discontinuities: No ____ Yes ____ Type of Fill ____

BEDDING / FOLLATION (Check one)

Strike ____ Dip ____

Thickness: V. Thin ____ Thin ____ Medium ____ Thick ____ V. Thick ____

AREA OUTCROPS (if applicable) Location ____

Veins ____ Type ____ Brecciation ____

Slickensides ____

Gouge ____ Color ____ Type ____

FIELD HARDNESS	WEATHERING	BEDDING / JOINT SPACING	ROCK CORE FRACTURING
V. Hard - Knife can't scratch	Fresh - Crystals bright	V. Thin / V. Close < 2"	V. Severe - Core < 1"
Hard - Scratches difficult	V. Slight - Joints slightly stained	Thin / Close 2" - 12"	Severe - Core 1" - 2"
Mod. Hard - Scratches readily	Slight - Joints completely stained	Medium / Mod. Close 12" - 36"	Moderate - Core 2" - 4"
Medium - Grooves difficult	Moderate - Core slightly discolored	Thick / Wide 36" - 120"	Slight - Core 4" - 8"
Soft - Grooves readily	Mod. Severe - Core completely discolored	V. Thick / V. Wide > 120"	V. Slight - Core > 8"
V. Soft - Carves	Severe - Strength reduced		
	V. Severe - Only rock fragments		
	Complete - Reduced to soil		

Source: Haley and Aldrich, Inc.

Figure B-1

Field Summary of Rock Characteristics.

Section *Worden Fm. along Rt. 33 in Ringwood Canyon* Unit *7*

Measured thickness *28 m* Attitude *N15W 65W*

Measured by *M. Lawry* Date *2 Apr84* Comments *V. well exposed. Better fossil collections can be made.*

Rock or sediment name: *Sandstone, subquartzose, feldspathic*

Color moist: *v. pale brn 10YR 7/3* dry: *" " " 10YR 8/3*

Bedding: distinct vague

Thicknesses beds: 5 m 1 m .1 m 1 cm 1 mm laminations:

Fossils:

Primary structures: *Planar x-bedding local; large burrows abundant -- unit 60 – 75 % bioturbated.*

Grain sizes range: 512 128 32 8 2 .5 .13 .03 .003
median: 256 64 16 4 1 mm .25 .06 .015 .004

Degree of sorting: very well well moderate poor very poor

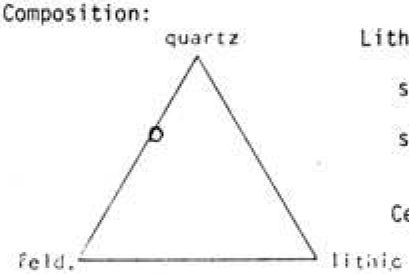
Grain shapes: very angular angular subangular subrounded rounded

Packing: loose moderate tight pressed

Fabric: *Fossils and sparse (3%) mica are locally planar (where not bioturbated)*

Weathering degree much none
depth 100 m 10 m 1 m

Composition:



Lithic clasts: granite *2-4%* chert aplite qzt slate argillite hornfels ls dol schist ss basalt rhyolite

Cement: *~25%* cal dol qz opal clay Fe-oxide gyp tar anhyd zeolite

Source: Compton (1985)

Figure B-2

Check Sheet for Describing Measured Stratigraphic Units.

Discontinuity	Definition	Characteristics
Fracture	A separation in the rock mass, a break.	Signifies joints, faults, slickensides, foliations, and cleavage.
Joint	A fracture along which essentially no displacement has occurred.	Most common defect encountered. Present in most formations in some geometric pattern related to rock type and stress field. Open joints allow free movement of water, increasing decomposition rate of mass. Tight joints resist weathering and the mass decomposes uniformly.
Faults	A fracture along which displacement has occurred due to tectonic activity.	Fault zone usually consists of crushed and sheared rock through which water can move relatively freely, increasing weathering. Waterlogged zones of crushed rock are a cause of *running ground* in tunnels.
Slickensides	Preexisting failure surface; from faulting, landslides, expansion.	Shiny, polished surfaces with striations. Often the weakest elements in a mass, since strength is often near residual.
Foliation planes	Continuous foliation surface results from orientation of mineral grains during metamorphism.	Can be present as open joints or merely orientations without openings. Strength and deformation relate to the orientation of applied stress to the foliations.
Foliation shear	Shear zone resulting from folding or stress relief.	Thin zones of gouge and crushed rock occur along the weaker layers in metamorphic rocks.
Cleavage	Stress fractures from folding.	Found primarily in shales and slates; usually very closely spaced.
Bedding planes	Contacts between sedimentary rocks.	Often are zones containing weak materials such as lignite or montmorillonite clays.
Mylonite	Intensely sheared zone.	Strong laminations; original mineral constituents and fabric crushed and pulverized.
Cavities	Openings in soluble rocks resulting from groundwater movement, or in igneous rocks from gas pockets.	In limestone range from caverns to tubes. In rhyolite and other igneous rocks range from voids of various sizes to tubes.

Source: Hunt (1984)

Figure B-3

Rock-mass Discontinuities.

Joints	Characteristics
Joint type	
Longitudinal	Parallels bedding or foliation planes
Normal or cross	Intersects bedding or foliations at right angles
Diagonal or oblique	Intersects bedding or foliations obliquely
Foliation	Parallels foliations
Curvilinear	Forms parallel sheets or slabs; often curved
Joint systems	
Joint set	Group of parallel joints
Joint system	Two or more sets or a group of joints with a characteristic pattern
Conjugate system	Two intersecting sets of continuous joints
Orthogonal system	Three sets intersecting at right angles
Cubic system	Forming cubes
Rhombic	Three sets parallel but with unequal adjacent sides and oblique angles
Pyramidal	Sets intersecting at acute angles to form wedges
Columnar	Divide mass into columns; three- to eight-sided, ideally hexagonal
Intense	Badly crushed and broken rock without system; various shapes and sizes of blocks

Source: Hunt (1984)

Figure B-4

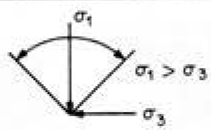
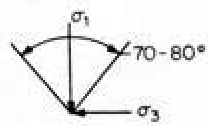
Geologic Nomenclature for Joints.

Surface	Roughness	Origin
Undulating	Rough or irregular Smooth Slickensided	Tension joints, sheeting, bedding Sheeting, nonplanar foliation, bedding Faulting or landsliding
Planar	Rough or irregular Smooth Slickensided	Tension joints, sheeting, bedding Shear joints, foliation, bedding Faulting and landsliding

Source: Hunt (1984)

Figure B-5

Classification of Joint Surface Roughness.

Characteristics	Shear joints	Displacement joints	Tension joints
Evenness	Very even	Even to uneven	Rarely even
Roughness	Smooth to mirror smooth	Smooth to rough	Rough
Degree of joint continuity	High	Medium	Low
Length of joint	Faults to very large joints	Very large joints to small joints	Large joints to small joints
Joint opening	Close	Variable	Wide
Fill material	Mylonite	Product of abrasion	
Traces of movement	Slickensides		
Fractures on molecular scale	Shearing of mesh	Fracture of crystallites	Fracture of crystallites
Orientation with respect to microstructure	Diagonal joints	Diagonal joints	Transverse joints = ac joints Longitudinal joints = bc joints Sedimentation joints = ab joints
Fracture angle 2α			
Friction angle (in unrestrained dilatation)			
Initial (peak)		30 to 55°	40 to 55°
Residual	About 15 to 30°	20 to 40°	30 to 45°

*From Fecker (1978).[30]

Source: Hunt (1984)

Figure B-6

Characteristics of Different Joint Sets in Hard Rocks.

Feature	Characteristics
Stratum discontinuity	Abrupt change in strata; discontinuous, omitted, or repeated
Slickensides	Polished and striated surfaces resulting from shearing forces; characteristic of weaker rocks.
Breccia	Angular to subangular fragments in a finely crushed matrix in the fault zone in strong rocks.
Gouge	Pulverized material along the fault zone; typically clayey; characteristic of stronger rocks.
Mineral alteration	Groundwater deposits minerals in the pervious fault zone, often substantially different from the local rock. Circulating waters can also remove materials. Radiometric dating of the altered minerals aids in dating the fault movement.
Groundwater levels	Clayey gouge causes a groundwater barrier and results in a water table of varying depths on each side of the fault. The difference in water levels can result in a marked difference in vegetation on either side of the fault, especially in an arid climate. Tree lines in arid climates often follow faults.
Foliation shear	Short faults caused by folding result in foliation shear in weaker layers in metamorphic rocks (typically mica, chlorite, talc, or graphite schist in a sequence of harder massive rocks) [Deere (1974)[14a]]. Shear zone thickness typically a few centimeters including the gouge and crushed rock. Adjacent rock is often heavily jointed, altered, and slightly sheared for a meter or so on each side. The zones can be continuous for several hundred meters and can be spaced through the rock mass.
Shale mylonite seam	A bedding shear zone caused by differential movement between beds of sedimentary rock during folding or during relief of lateral stress by valley cutting. Concentrated in the weaker beds such as shale, or along a thin seam of montmorillonite or lignite, and bounded by stronger beds such as sandstone or limestone. Sheared and crushed shale gouge is usually only a few centimeters thick but it can be continuous for many tens of meters [Deere (1974)[14a]]. Both foliation shear and mylonite, when present in slopes, represent potential failure surfaces.

Source: Hunt (1984)

Figure B-7

Internal Evidence of Faulting.

Feature	Characteristics	Fault type
Lineations	Strong rectilinear features of significant extent are indicative but not proof. Can also represent dikes, joints, foliations, bedding planes, etc. (Fig. 2.8).	All types
Landforms		
Scarps	Long, relatively smooth-faced, steep-sided cliffs.	Normal
Truncated ridges	Lateral displacement of ridges and other geomorphic features.	Wrench
Faceted spurs	Erosion-dissected slopes form a series of triangular-shaped faces on the foot wall.	Normal
Horst and graben	Block faulting. A sunken block caused by downfaulting or uplifting of adjacent areas forms a rift valley (graben). An uplifted block between two faults forms a horst. Soils forming in the valley are more recent than those on the uplands. Examples: Lake George, New York; Dead Sea; Gulf of Suez; Rhine Valley, West Germany; Great Rift Valley of Kenya; parts of Paraiba River, Sao Paulo, Brazil.	Normal
Drainage		
Rejuvenated streams	Direction of flow reversed by tilting.	Normal
Blocked or truncated	Flow path blocked by scarp and takes new direction.	Normal
Offset	Flow path offset laterally.	Wrench
Sag pond	Lakes formed by blocked drainage.	Normal
Secondary features	Practically disappear within less than 10 years in moist climates, but may last longer in dry [Oakeshott (1973)[13b]].	
Mole tracks	En-echelon mounds of heaved ground near base of thrust fault or along wrench fault.	Thrust, wrench
Step-scarps	En-echelon fractures form behind the scarp crest in a reverse fault (tension cracks).	Normal
Seismological	Alignment of epicenters.	All types

Source: Hunt (1984)

Figure B-8

Surface Evidence of Faulting.

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SECTION 3.8   LABORATORY TESTS FOR SOIL

SECTION 3.8
LABORATORY TESTS FOR SOIL

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3.8 LABORATORY TESTS FOR SOIL

3.8-0 INTRODUCTION

The purpose of this section is to provide general guidelines for the selection of certain applicable laboratory tests on soil samples. These laboratory tests provide physical properties of soils, which may be necessary for geotechnical or hydrogeologic investigations, feasibility studies, and remedial design evaluations. The tests can be categorized in two general types: Index Properties Testing and Engineering Properties Testing. Index testing, such as grain size distribution, water content, specific gravity, and organic content provide the basic properties of a soil mass and are generally used for classification purposes. Some index properties are used to determine other index properties, such as porosity, as well as for correlation with engineering properties. Geotechnical properties such as compressibility, shear strength, permeability, and moisture/density relationships are necessary to predict the behavior and performance of soils used in earth construction. Typical applications for geotechnical laboratory testing include the following:

- Index properties and permeability testing are used in hydrogeologic investigations to help characterize ground water or contaminant flow behavior through various geologic media.

- Moisture density testing, permeability testing and Atterberg limit testing are used to establish the unique relationship between soil placement criteria and resulting permeability for each site considered. Examples of use are the design and construction of landfill soil liners and cover systems.

- Compressibility, permeability, and strength of soils and/or wastes are engineering property tests utilized for landfill designs. Highly compressible waste materials can result in surface subsidence, which damages cover systems. The permeability of the waste materials determines rates of waste consolidation and leachate generation. The properties of the waste materials determine how they can be graded, sloped, drained, and traveled on. Representative laboratory testing can only be performed on waste materials that could be considered homogenous in engineering analyses such as homogenous paper mill sludges or tannery waste. Representative laboratory testing cannot be performed on heterogeneous wastes with standard equipment currently used.

- Shear strength of soil materials must be determined to evaluate the stability of existing and new waste containment dikes. Consolidation tests are important if the soils underlying the dikes are soft and compressible. These tests are useful for evaluating liner integrity, leachate collection system and construction sequencing.

For each test method, there is a discussion of the significance and use of the test, physical properties obtained, field methods required for obtaining samples, sample size, preservation of samples, and special considerations, where it is relevant.

ASTM refers to the American Society for Testing and Materials. Geotechnical laboratory test procedures are described in the annual book of ASTM Standards, Section 4, Volume 04.08. COE EM refers to the Engineer Manual for Laboratory Soils Testing prepared by the U.S. Army Corps of Engineers, Waterways Experiment Station under direction from the Office, Chief of Engineers, May 1, 1980, Edition.

3.8-1 GRAIN-SIZE ANALYSIS

3.8-1.1 Standard Test Methods

The American Society of Testing Materials (ASTM) method numbers utilized are:

- C 117:Standard Test Method for Material Finer than 75 mm (200) Sieve and Mineral Aggregate by Washing
- C 136:Standard Test Method for Sieve Analysis for Fine and Coarse Aggregate
- D 1140:Standard Method for Amount of Material in Soils Finer than Sieve Number 200 (75 mm)
- D 421:Standard Practice Dry Preparation of Soil Samples for Particle Size Analysis and Determination of Soil Constraints
- D 422:Standard Method for Particle Size Analysis of Soils

3.8-1.2 Significance and Use

A grain-size analysis provides a distribution of soil particle sizes by weight. The grain-size distribution of medium- to coarse-grained soils (particles larger than 0.075 millimeter in diameter) is determined directly by mechanical analysis, while that of fine-grained soils (generally particles less than 0.075 millimeters in diameter) is determined indirectly by hydrometer analysis (sedimentation). Typical instances in which a grain-size distribution would be useful are in soil classification, rough estimations of the permeability of uniform, coarse-grained materials using published correlations, estimation of soil drainage characteristics, and evaluation of soil suitability for construction purposes.

3.8-1.3 Physical Parameters Obtained

The physical parameter obtained from grain size analysis is:

- o Particle Size Distribution - a plot of the distribution of the particle size by weight on a logarithmic scale; coefficient of uniformity, percent fines, and maximum particle size.

3.8-1.4 Field Sampling Methods, Sample Size and Preservation

Samples for the grain-size analysis may be obtained using standard drilling and test pit sampling techniques, such as split-spoon sampling. Representative samples of coarser-grained soils (gravels) may not be obtained with the standard split-spoon sampler due to the standard inside diameter of the split spoon of 3.5 cm. Undisturbed samples are not necessary. Sample size is dependent on the maximum particle size of the material to be tested and is listed on Table 3.8-1.

Prior to testing, store samples in noncorrosible, airtight containers in accordance with ASTM D 4220-89 (Standard Practice for Preserving and Transporting Samples).

3.8-2 SPECIFIC GRAVITY OF SOIL

3.8-2.1 Standard Test Method

The ASTM method number utilized is:

- o D 854:Standard Test Method for Specific Gravity of Soils

3.8-2.2 Significance and Use

The specific gravity of soil is defined as the ratio of a unit weight of a soil's solid particles to the unit weight of water. The specific gravity of the material is used, in conjunction with other index properties, for determination of the unit weight of a particular soil and for classification purposes. This index property is also used in the determination of other index and engineering properties of soil, including void ratio and porosity.

3.8-2.3 Physical Parameters Obtained

The physical parameter obtained by specificity is:

- o G_s = Specific Gravity of Solids, no units

3.8-2.4 Field Sampling Methods, Sample Size, and Preservation

Samples for specific gravity determinations may be obtained using standard drilling and test pit sampling techniques. Collection of undisturbed samples is not required. Sample size is dependent on the apparatus used in the determination and ranges between 10 and 25 grams.

Prior to testing, store samples in noncorrodible, airtight containers in accordance with procedures outlined in ASTM D 4220-89.

3.8-2.5 Special Considerations

The term "solid particles" is typically assumed to mean naturally occurring mineral particles that are not soluble in water. The specific gravity of materials containing extraneous matter (such as contaminants, cement, or lime) and soils containing materials with a specific gravity of less than one, such as oil residue, typically require special treatment or a qualified definition of specific gravity.

3.8-3 ATTERBERG LIMITS

3.8-3.1 Standard Test Method

The ASTM method number utilized is:

- D 4318:Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

3.8-3.2 Significance and Use

Atterberg limits are index properties applicable to cohesive soils only (clays and silts) and are used to describe a soil's plasticity. Atterberg limits are used most commonly for soil classification purposes, although several empirical relationships between Atterberg limits and engineering properties have been developed.

By comparing the Atterberg limit values with the water content of the in-situ material, one can judge the workability and constructability of a particular soil. This relationship is important in the compaction of clay liners and cover systems for landfills.

3.8-3.3 Physical Parameters Obtained

The physical parameters obtained from Atterberg limits are as follows:

- LL = Liquid Limit - The water content, in percent, of a soil at the arbitrarily defined boundary between the liquid and plastic states.

- PL = Plastic Limit - The water content at which a soil can no longer be deformed by rolling into 3 mm (1/8-inch) diameter threads without crumbling.

- PI = Plastic Index - The range of water content for a soil where it behaves as a plastic material. Numerically, it is the difference between the liquid limit and plastic limit.

3.8-3.4 Field Sampling Methods, Sample Size, and Preservation

Samples for this test may be obtained using standard drilling and test pit sampling techniques. Undisturbed sampling techniques are not necessary. Obtain a sample sufficient to provide 150 to 200 grams of material, which is less than 0.425 mm in diameter.

Prior to testing, store samples in noncorrodible, airtight containers in accordance with procedures outlined in ASTM D 4220-89.

3.8-3.5 Special Consideration

The liquid and plastic limits of many soils that have been allowed to dry before testing may be considerably different from values obtained on undried samples. If the liquid and plastic limits of soils are used to correlate or estimate the engineering behavior of soils in their natural moist state, do not permit samples to dry before testing, unless data on dried samples are specifically desired.

The composition and concentration of soluble salts, chemicals or contamination in a soil may affect the values of the liquid and plastic limits of soils as well as the water content values.

3.8-4 MOISTURE CONTENT

3.8-4.1 Standard Test Method

The ASTM method number utilized is:

- D 2216:Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock

3.8-4.2 Significance and Use

The water content of a soil is the ratio of the weight of water of a given soil mass to the weight of solid particles. The water content of a soil is used in expressing the phase relationship of air, water, and solids in a given volume of material. The water content of cohesive soils is empirically correlated to compressibility, permeability, density, and workability.

3.8-4.3 Physical Parameters Obtained

The physical parameter obtained from a moisture content test is:

- w = Water Content, expressed as a percent

3.8-4.4 Field Sampling Methods, Sample Size, and Preservation

The sample size for water content determination is dependent on the purpose of the test, the material being tested, and the type of sample (specimen from another test, bag, tube, or split barrel). In all cases, however, select a representative portion of the total sample. If a layered soil or more than one soil type is encountered, select an average portion, or individual portions of both, and note which portions were tested in the report of the results. For bulk samples, select the test specimen after it has been thoroughly mixed. The mass of moist material selected should be in accordance with Table 3.8-2.

For cohensionless soils, mix the material and then select a test specimen size from Table 3.8-2. For cohesive soils, the mass of the moist material should not be less than 25 grams or should be in accordance with Table 3.8-2.

Prior to testing, keep the samples in noncorrodible, airtight containers in accordance with procedures outlined in ASTM D 4220-89 at a temperature between 3 and 30 degrees Celsius and in an area that prevents direct contact with sunlight.

3.8-4.5 Special Considerations

This method does not give truly representative results for materials containing significant amounts of halloysite, montmorillonite or gypsum; highly organic soils; or materials in which the pore water contains dissolved solids (such as salt in the case of marine deposits). For material of the previously mentioned types, a modified method of testing or data calculation may be established to give results consistent with the purpose of the test.

3.8-5 ORGANIC CONTENT

3.8-5.1 Standard Test Method

The ASTM method number utilized is:

- o D 2974:Standard Test Method for Moisture, Ash and Organic Matter of Peat and Other Organic Soils

3.8-5.2 Significance and Use

The organic content determination measures the percentage of moisture, ash, and organic matter contained in a given sample. The organic content of a soil is primarily used for classification purposes and can significantly affect other index and engineering properties of a soil. Materials with high organic contents typically have low shear strength and are very compressible. The organic content of a soil or waste material can have a significant impact on the cost of incineration processes or off-site disposal. It also is an influencing factor in the biotransformation of organic contaminants.

3.8-5.3 Physical Parameters Obtained

The physical parameter obtained by an organic content analysis is:

- Oc = Organic Content - the ratio of the weight of organics in a given soil mass to the total weight of the soil mass. Expressed as a percentage.

3.8-5.4 Field Sampling Methods, Sample Size, and Preservation

Samples for the organic content determination may be obtained using standard drilling and test pit sampling techniques. Undisturbed sampling techniques are not necessary. Minimum sample size should range between 50 and 100 grams.

Prior to testing, store samples in noncorrodible, airtight containers in accordance with procedures outlined in ASTM D 4220-89.

3.8-6 MOISTURE-DENSITY RELATIONSHIPS OF SOILS (LABORATORY COMPACTION TEST)

3.8-6.1 Standard Test Methods

The ASTM method numbers utilized are:

- D-698:Standard Test Method for Moisture-Density Relations of Soil Aggregate Mixture, Using 5.5 lbs. (2.49 kg) Rammer and 12 Inch (305 mm) Drop

- D-1557:Standard Test Method for Moisture-Density Relations Soil and Soil Aggregate Mixtures, Using 10 lbs. (4.54 kg) Rammer and 18 Inch (457 mm) Drop

3.8-6.2 Significance and Use

The purpose of a laboratory compaction test is to determine the moisture/ density relationship of a representative soil sample. This relationship is used as the standard for evaluating the effectiveness of compaction processes in the field. This test is generally not performed until specific materials for construction have been identified. The test is performed on fine-grained and coarse-grained soils. For design and construction of soil liners and cover systems, a series of laboratory permeability tests are often performed together with the laboratory compaction test to establish a relationship between moisture content, soil density, and permeability.

3.8-6.3 Physical Parameters Obtained

The physical parameters obtained from a laboratory compaction test are:

- ∂_d =dry density - weight per unit volume, dry; expressed as Mg/m^3.

- ∂_w =wet density - weight per unit volume, with water; expressed as Mg/m^3.

- o ∂_d max =maximum dry density - the maximum unit weight determined in the lab) produced on a particular soil under a particular compaction effort; this density is considered the maximum density that can be obtained in the field, using commonly used compaction equipment; expressed as Mg/m^3 (lbs/ft^2).

- o OMC =Optimum Moisture Content - moisture content (of a soil) corresponding to the maximum density; expressed as a percentage.

3.8-6.4 Field Sampling Methods, Sample Size, and Preservation

Due to the large sample size required, samples for moisture density testing are generally obtained using standard test pit techniques. Sample size is dependent on the method used and should range between 20 and 50 kilograms of material.

Samples stored prior to testing must be sealed to prevent moisture loss in accordance with D 4220-89.

3.8-7 STRENGTH TESTING OF SOILS

3.8-7.1 Standard Test Methods

The ASTM method numbers utilized are:

- o D 2166:Standard Test Method for Unconfined Compressive Strength of Cohesive Soils

- o D 2850:Standard Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression

- o D 3080:Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions

The methods utilized by the US Army Corps of Engineers, Engineer Manual for Laboratory Soils Testin (COE EM) are:

- o COE EM 1110-2-1906 (Appendix IX): Drained Direct Shear Test
- o COE EM 1110-2-1906 (Appendix X) : Triaxial Compression Tests
- o COE EM 1110-2-1906 (Appendix XI): Unconfined Compression Test

3.8-7.2 Significance and Use

Strength testing of soils is necessary for stability evaluations of earth embankments, excavations, and soils supporting structure foundations. For landfill projects, strength tests on homogeneous waste materials are useful for evaluation of waste handling, placement, configuration, and construction sequencing. Strength tests are often performed in preliminary stages of projects to evaluate conceptual remediation alternatives or preliminary design for waste containment schemes, closure evaluations, site clean-up schemes, and new landfills. For final design phases of such projects, strength testing is imperative.

Several different types of triaxial strength testing can be performed depending on the intended use of the soil and expected loading conditions. The selection and use of soil strength testing will depend on the project size and the size of the investigation. In general, a specific type of strength test will be selected for a particular soil or waste material depending on loading conditions that will be experienced during construction and operation. To assure that the type of strength test planned corresponds to the anticipated loading conditions, consult a geotechnical engineer.

3.8-7.3 Physical Parameters Obtained:

The physical parameters obtained by strength testing are:

- c =cohesion - the shear strength that exists in the absence of any normal stress on a failure plane; expressed in kPa.
- $q\mu$ = unconfined compressive strength; expressed in kPa.
- Φ =angle of internal friction; expressed in degrees.

3.8-7.4 Field Sampling Methods, Sample Size, and Preservation

Samples for strength testing may be obtained using drilling and test pit sampling techniques for disturbed and undisturbed sampling. Perform testing on disturbed samples if soils are to be used for construction purposes (i.e., reworked during construction). Perform testing on undisturbed samples if the native (in-situ soils) are to be loaded during construction (i.e. embankments or landfills are to be constructed over existing soils).

The most common means of undisturbed sampling is by thin-walled tube sampling methods outlined in Section 3.4 of these references. In order to minimize sample disturbance, thin walled sampling tubes should be no smaller than 7.62 cm. (3-inches) in diameter. It is important to minimize sample disturbance to obtain accurate strength test information. Disturbed (remolded) test specimens can also be made from samples obtained in standard drilling and test pit sampling techniques.

Seal samples to prevent moisture loss and handle carefully during shipment to avoid disturbance, in accordance with procedures outlined in ASTM D 4220-89.

3.8-8 CONSOLIDATION TEST

3.8-8.1 Standard Test Method

The ASTM method number utilized is:

- o D 2435: Standard Test Method for One Dimensional Consolidation Properties of Soils

3.8-8.2 Significance and Use

Consolidation testing of soils will provide the parameters necessary to predict the rate and magnitude a soil will consolidate (settle) under the application of a load. The test is usually performed on fine-grained, compressible soils such as silts and clays. A typical instance in which the rate and magnitude of settlement would need to be determined is an evaluation of the impact of a landfill and its embankments upon underlying soils. If a particular waste can be considered to behave as a homogeneous mass, consolidation testing may be helpful to predict the amount of settling a landfill cap many undergo due to the overlying weight of the cap material. Consolidation properties are also necessary to predict the amount of leachate that may be generated from the landfill waste.

3.8-8.3 Physical Parameters Obtained

Some of the physical parameters obtained from the consolidation test are:

- o c_v = Coefficient of Consolidation - used to determine the rate of consolidation of a soil; expressed as m^2/year.
- o C_c and C_r = Compression Indices - used to determine the amount of settlement a soil will experience under application of a load; dimensionless.
- o e_o = Initial or In-situ Void Ratio used in the calculation of settlement; dimensionless.

3.8-8.4 Field Sampling Methods, Sample Size, and Preservation

Samples for consolidation testing must be obtained using drilling and test pit sampling techniques for undisturbed sampling. The most common means of undisturbed sampling is by thin-walled tube sampling methods outlined in Section 3.4 of these references. In order to minimize the effects of sampling on the test results, thin-walled sampling tubes should be no smaller than 7.62 cm. (3-inches) in diameter. Alternative means of sampling shallow soils (usually less than 3 meters) would be by test pitting techniques outlined in Section 3.1 of these SRs.

Seal the samples to prevent moisture loss and handle carefully during shipment, following procedures outlined in ASTM D 4220-89.

3.8-9 PERMEABILITY OF SOILS

3.8-9.1 Standard Test Methods

The ASTM method number utilized is:

> D-2434: Standard Test Method for Granular Soils (Constant-Head Test)

The COE EM method number utilized is:

> COE EM 1110-2-1906 (Appendix VII): Method for Granular Soils and Cohesive Soils

3.8-9.2 Significance and Use

Permeability testing of soils will provide parameters necessary to predict the flow rate of a fluid through soils. Laboratory permeability tests can be performed on "undisturbed samples" or on samples recompacted in the lab to approximate in-situ conditions. Permeability tests are used extensively in hydrogeologic investigations to help predict the rate of groundwater flow or contaminant migration.

3.8-9.3 Physical Parameters Obtained

The physical parameter obtained in permeability testing is:

> K = coefficient of hydraulic conductivity; permeability;
> expressed as cm/sec.

3.8-9.4 Field Sampling Methods, Sample Size, and Preservation

Samples for permeability testing may be obtained using standard drilling and test pit sampling techniques for disturbed and undisturbed sampling. The sample size should range between 400 and 1600 grams.

Prior to testing, store samples in noncorrosive, airtight containers in accordance with ASTM D 4220-89.

3.8-9.5 Special Considerations

The test method and equipment apparatus used for permeability testing can vary considerably depending on the condition and character of the sample to be tested. Whether the sample is fine-grained or coarse-grained; very soft, undisturbed, remolded or compacted; saturated or non-saturated, will influence the type of apparatus and test method employed.

Maximum Particle Size		Minimum Weight of Samples	
((mm)	((inches)	(g)	((lbs.)
75.00	3.0	5000	11.00
50.00	2.0	4000	9.00
25.00	1.0	2000	4.50
12.50	0.5	1000	2.20
4.75	0.2	200	0.50
2.00	0.1	100	0.25

Table 3.8-1

Sample Size Needed to Analyze for Various Maximum Particle Sizes in Test for Grain-size Analysis.

Sieve Retaining More Than about 10% of Sample (mm)	Recommended Minimum Mass of Moist Specimen (grams)
2.00	100 to 200
4.75	300 to 500
19.00	500 to 1000
38.00	1500 to 3000
76.00	5000 to 10000

Table 3.8-2

Mass of Moist Specimen Recommended for Different Sieve Sizes.

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SECTION 3.9 PLUGGING BOREHOLES

SECTION 3.9
PLUGGING BOREHOLES

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3.9 PLUGGING BOREHOLES

3.9-1 PURPOSE

The purpose of plugging boreholes is to maintain the integrity of the natural subsurface conditions. Subsurface exploration activities of any kind introduce the potential to develop pathways for the movement of liquids and gases between geologic materials. Boreholes are the most common technique used for subsurface exploration associated with geotechnical investigations, soil and rock sampling, down-hole geophysical exploration, and the installation of piezometers and monitoring wells. The most common drilling techniques for making boreholes include, but are not limited to, uncased mud rotary, cased drive-and-wash and spun methods, and solid- and hollow-stem augers. In most cases, the concern is to prevent the migration of contaminants between geologic strata or from the surface to the subsurface environment. In addition to the potential migration of contaminants, boreholes may impact the natural water levels in both confined and unconfined aquifers. For these reasons, it is recommended that all boreholes that are not sealed as part of the installation of either piezometers or monitoring wells be plugged immediately after completion and utilization for their intended purpose. This should apply to uncontaminated as well as contaminated areas.

A brief description of the most common methods and materials used to plug boreholes are discussed in the following subsection. Some of the methods are also discussed in Section 3.3, Borings in Contaminated Areas, Section 4.3, Well Installation Procedures, and Section 4.6, Decommissioning of Monitoring Wells.

3.9-2 METHODOLOGY

The principle behind the methodology is simple and straightforward: that is, to plug borehole from bottom to top with a permanent, low permeability material. The most commonly used plugging material is described in this section. Because different equipment may be used to advance the borehole, this section will also describe a plugging methodology for the three most common drilling techniques: mud rotary, spun and drive-and-wash casing, and solid- and hollow-stem auger.

3.9-1.2 Plugging Material

It is recommended that the grout mixture used to plug all boreholes be composed, by weight, of 20 parts Portland cement to one part of bentonite, with a maximum of 8 gallons of water per 94-pound bag of cement. More bentonite may be required if the formation is very porous. This ratio of cement to bentonite should not exceed 6:1. Only clean water should be used when mixing grout slurries. It is important to always mix the bentonite with the water first, before adding cement. More details of grout material, mixtures, and mixing methods are described in Section 4.3-5.3.2 Grout Slurries. It should be noted that a neat cement is recommended for decommissioning abandoned wells when the riser and screen are left in place (Section 4.6).

3.9-2.2 Installation Techniques

The following sections briefly describe the plugging methods for mud rotary, cased boring, and solid- and hollow-stem auger techniques.

3.9-2.2.1 Mud Rotary Boreholes

When an uncased mud rotary borehole is completed, the plugging may be accomplished by pumping the selected grout mixture down the drill pipe while it is still in place with the rotary bit at the bottom of the hole. Because the grout mixture may plug the drill bit, it is recommended to use a separate tremie tube for this procedure. A tremie tube is a small diameter hollow plastic or metal tube. While grout is being pumped down the borehole, the drilling mud and formation water escape at the surface between the drill pipe and borehole wall (annular space). Grout should be pumped continuously until all the drilling mud and ground water has been forced out of the borehole. This is usually determined visually by watching the escaping fluid. When the hole has been completely filled with grout, the drill pipe can be removed. As the pipe is removed from the hole, the level of grout should be maintained at the ground surface. This can be accomplished by either pumping more grout down the drill pipe or by pumping grout directly into the annular space around the drill pipe. The latter is much easier and should be done with a short (i.e., 5 to 10 foot long) tremie tube. After the drill pipe has been completely removed, the grout level should be observed and periodically "topped off" with additional grout as settling and curing occurs.

3.9-2.2.2 Cased Boreholes

Cased borings are generally drilled with either spun or drive-and-wash techniques. When completed, even if they are above the water table, they generally have residual water from the washing activities in the casing. Plugging should be accomplished by pumping the selected grout mixture to the bottom of the borehole through a tremie tube. As the borehole fills, the residual water in the casing will be displaced and escape out the top of the casing. Grout should be pumped continuously until all the wash water has been forced out of the casing. This is usually determined visually by watching the escaping fluid. When the casing is full, the casing can be pulled from the borehole. As each section of casing is removed, the grout level should be maintained at the top. While the casing is being pulled, the tremie pipe can be shortened by 5- or 10-foot lengths.

3.9-2.2.3 Auger Boreholes

Auger borings are drilled using either a solid- or hollow-stem technique. Solid-stem augers should only be used under special conditions when it has been determined that plugging of the borehole will not be required. In order to plug a borehole made with a solid-stem auger, the auger must be totally removed from the ground prior to grouting. In unstable soil conditions, the borehole may collapse partially or completely before a tremie tube can be inserted. Every attempt to pump grout into the uncollapsed portion of the borehole must be made immediately after the solid stem auger has been removed. The procedure utilized to plug the borehole is the same as for the Hollow-stem auger, below, except there are no augers to be removed during the process.

Hollow-stem auger borings are plugged in much the same way as a cased boring. If the augers are below the water table, a tremie tube must be used to pump the grout to the bottom of the hole. The grout will displace and force the formation water out the top of the augers. The augers can be pulled and removed, one section at a time, while the level of grout is maintained at the top. If possible, it is advisable to pull the augers without rotating them. This will produce a smoother borehole wall and thus maintain a more uniform column of grout.

If the augers are above the water table, it is acceptable to pour grout into the hollow stem directly. Always keep the grout filled to the top as auger sections are pulled and removed.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 4.1 MONITORING WELL NETWORK DESIGN

SECTION 4.1
MONITORING WELL NETWORK DESIGN

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SECTION 4.1 MONITORING WELL NETWORK DESIGN

4.1-1 PURPOSE

The following section presents guidelines for the design of monitoring well networks. Monitoring wells are installed for a variety of reasons including:

- To determine horizontal and vertical hydraulic gradients that influence the direction of ground water flow.
- To obtain measurements of aquifer properties, primarily hydraulic conductivity, utilizing in-situ hydraulic conductivity tests and pump tests.
- To monitor changes in water quality over time.
- To define the two- or three-dimensional distribution of contamination in an aquifer.
- To evaluate the effectiveness of remedial measures.

Frequently, not enough attention is given in field investigation programs to the design of well networks. If the network is not properly designed, important features relating to both the hydrogeology and chemical composition of the water within an aquifer may not be gathered. If this occurs, one might reach erroneous conclusions about conditions at the site. This could result in inadequate definition of potential receptors and improper design of remedial measures.

The design of a monitoring well network is site-specific. It is important to understand that the conditions at each site are unique and, therefore, site-specific factors affecting ground water flow and contaminant migration must be considered when designing an appropriate monitoring well network. It also makes a difference whether the network is being designed to define a plume of contamination migrating from a known source or to identify a source from a downgradient point or area of contamination. Design of a network requires input from experienced individuals familiar with the interrelationships of geology, hydrology, and ground water chemistry, as well as the suitability of various drilling and well installation methods.

This section will focus on designing well networks for contaminant plume investigations and not networks specifically used to gather pump test data. Guidance on the design of pump test monitoring systems is available from the DEP, Bureau of Resource Protection, Division of Water Supply. However, it should be noted that the two are not mutually exclusive. Certain sites may involve conducting a pump test at some phase of the contaminant investigation.

4.1-2 DESIGN CONSIDERATIONS

The following factors should be considered in the development of a network design:

- The objective(s) of the investigation.
- Data collected from the wells must be representative of the aquifer conditions.
- A desire to maximize the information obtained from a limited number of wells.
- Flexibility - modification of the placement and design of monitoring wells must be possible, based on new information acquired in the field.
- Budget

4.1-2.1 Objective(s) of the Investigation

The objective(s) of the investigation must be clearly defined in order to design an effective monitoring well network. Generally, investigations can be divided into two categories: uncontaminated sites where hydrogeologic monitoring is required or hydraulic characteristics are to be evaluated and contaminated sites where both aquifer hydraulic characteristics and ground water chemistry must be evaluated.

4.1-2.1.1 Investigations at Uncontaminated Sites

Monitoring wells may be installed at uncontaminated sites to observe draw-down during a pump test, to perform slug tests in order to estimate hydraulic conductivity, to obtain water-level data to determine ground water gradients and flow directions, and to monitor the impact of various activities on the hydraulic head. In many cases ground water sampling is not required in these investigations. If ground water chemistry and contaminant characteristics are not a concern, then the network design may need to consider only the site geology and hydrology.

4.1-2.1.2 Investigations at Contaminated Sites

In many types of contamination investigations the best approach is to perform field studies in phases, incorporating an increasing level of complexity with each phase as more information concerning specific site conditions is collected and analyzed. The network becomes denser or more extensive with each successive phase. The network design will be influenced by the migration pattern of the contamination problem being investigated as well as by the chemistry of the contaminants. From a point of contamination where the source is unknown, the network design extends in the upgradient direction seeking to locate the source. From a known source of contamination, the network is designed to characterize the three-dimensional extent of the plume in the downgradient direction.

4.1-2.2 Collecting Representative Data

In designing a network for a site investigation, consideration must be given to the influence of the drilling techniques, well construction materials, well location, and installation depth to ensure that the environmental samples and analytical data generated from the wells are representative of the site. There are numerous cases where the conditions at a site have been improperly characterized due to introduction of chemicals during drilling and installation of monitoring wells.

4.1-2.3 Maximizing the Information with a Limited Number of Wells

With the exception of research sites, there are rarely enough data to thoroughly characterize a site. The primary reasons for this are that the understanding of subsurface processes is incomplete and the costs associated with subsurface studies and well installation programs are very high. Consequently, it is desirable to maximize the amount of information that can be collected from each borehole and well. If both water level and water quality data are being collected, then the well design should allow proper placement of wells so that contaminants are intercepted and adequate sizing so that sampling equipment can be lowered into the well. As the depth of the borehole increases, multi-level well installations become increasingly cost-effective.

In order to maximize the information obtained from a limited number of wells, it is important to monitor drilling progress continuously, to collect soil samples frequently, to evaluate the characteristics of the subsurface materials encountered, and to monitor the samples for contaminants. During the drilling process, if appropriate, estimation of the aquifer in-situ borehole permeability and visual classification of soil samples should be employed to evaluate variations in permeability and to determine the most suitable zone for installing the well screen.

4.1-2.4 Incorporating Flexibility in the Design

It is important that the initial design provides for modifications based on an evaluation of new data acquired during the field program. The final design must be based on an understanding of the subsurface geology and other site characteristics. Typically, collection of new subsurface information occurs concurrently with well installation programs. If existing site information is limited or if the field investigation reveals important differences from the original assumptions, the network design should be re-evaluated based on this new data. For example, the detection of separate phase liquids or identification of a highly permeable zone may require specific types of well installations or materials. If these considerations are not taken into account, the collection of appropriate information that is most relevant to the investigation may not be obtained. This might result in the omission of significant information about the site.

Final decisions on boring locations and well placement should be based on evaluation of the data acquired during the field program. Field personnel should have adequate experience and authority to make changes in the initial design when such changes are related to new information about field conditions. One should not hesitate to stop drilling to examine new data if it affects drilling locations. The cost of drilling one poorly located well far outweighs the cost of remobilizing the drilling rig in almost every case.

4.1-2.5 Budget Considerations

The amount of money available for subsurface investigations and well installations directly influences the network design. In order to get the most information for the available funds, data gaps existing at a site must be identified and prioritized before initiating a site investigation. Attempts should be made to fill the data gaps to the extent practicable. For example, if the site geology or hydrogeology is thought to be complex and the existing data is limited, it would be inappropriate to install only two wells containing a large number of expensive multi-level sampling instruments. For the same amount of money, several monitoring wells/piezometers might be installed across the site to provide more insight into the basic geologic and hydrogeologic conditions.

Too often, a disproportionate amount of funds are spent on chemical analytical work, leaving inadequate funds for an accurate characterization of the site hydrogeology. Even the most sophisticated analysis is useless if the wells have not been properly designed and located.

4.1-3 DEFINING THE PROBLEM

The scope of the network design is dependent on many factors including the extent of available information, the complexity of the site geology and hydrogeology, the proximity of downgradient receptors, the nature of the contaminants, if any, and access to and around the site. Proper network design requires a basic knowledge of the following factors:

- Physical setting.
- Character of the contaminants.
- Preliminary determination of exposure pathways.

Important aspects of each factor are discussed on the next page:

4.1-3.1 Understanding the Physical Setting

Characterizing the physical setting is often the first step taken prior choosing well locations and well types. Often this factor, more than any other, controls the final design of a well network.

4.1-3.1.1 Geology

In order to design an effective monitoring well network, the nature and variability of the site geology must be understood. Small-scale heterogeneities can have a significant impact on the movement of contaminants. Borings and monitoring wells should be positioned, if possible, so that geologic cross-sections can be constructed across a site at various locations and orientations (see Figure 4.1-1). Knowledge about the regional geologic history of a site is essential for accurate subsurface interpretations. In the more detailed phases of an investigation, information on grain-size, porosity, and permeability may be useful in refining a network design. Geophysical investigations also may be helpful in defining subsurface conditions.

4.1-3.1.2 Hydrogeology

An evaluation of the hydrogeology of the site is another fundamental aspect of network design. This information may range from an estimate of ground water flow directions based on a review of topographic map features to a detailed assessment of variations in horizontal and vertical gradients at the site and the interaction of the ground water with surface water features. The influence of nearby pumping wells and ground water sinks created by subsurface utilities also should be considered. An assessment of the hydrogeologic conditions at a site typically involves the construction of ground water contour maps, flow nets and permeability calculations (see Figure 4.1-2).

4.1-3.1.3 Existing Surface and Subsurface Structures

An assessment of significant surface and subsurface features is necessary for an effective network design. Dig-Safe should be contacted to determine the location of underground utilities in public right-of-way before initiating any subsurface investigations. Dig-safe requires at least three days notice and may or may not trace lines across private property. If applicable, local sewer and water departments should be contacted to locate municipal utilities. A site map showing private utilities should be obtained whenever possible. Man-made features such as overhead utilities and trees and buried utilities such as storm drains, septic tanks, and leaching fields, as well as property boundaries and roadways may significantly affect access to drilling sites and, hence, the placement of wells. Additionally, subsurface trenches and active pumping wells can significantly alter natural ground water flow directions and contaminant distribution.

4.1-3.1.4 Conceptual Model

Well networks should be based on a conceptual geologic and hydrogeologic model of the site conditions. In most investigations it is prudent to incorporate monitoring points that serve to prove or disprove the validity of this conceptual model. This may include wells placed in low permeability areas to provide quantification and validation of the actual permeability and to determine if contaminants, though not expected, are actually present.

It may also include placing wells at suspected recharge/discharge boundaries to establish ground water flow conditions. A complete conceptual model should incorporate both vertical and horizontal flow conditions (i.e. flow net). The importance of developing a conceptual model cannot be overemphasized.

4.1-3.2 Understanding the Physical and Chemical Characteristics of Contaminants

Characteristics of the natural ground water quality and any contaminants in the aquifer will affect the fate and transport of chemical species in the aquifer. Contaminants can be sub-divided into two main categories: aqueous dissolved phase liquids (ADPLs) and non-aqueous phase liquids (NAPLs); the latter group includes both "floaters" and "sinkers." Once an assessment has been made of the potential sources, the types of contaminants, and the suspected contaminant concentrations, information on the characteristics of each contaminant should be compiled. Important chemical characteristics that should be evaluated include solubility, specific gravity, viscosity, octanol/water partition coefficient, Henry's Law Constant, and degradation by-products. These characteristics influence the spatial distribution of the contaminant in the aquifer, how it reacts with water, and how it will migrate and degrade in the aquifer. These chemical characteristics must be taken into account when developing a monitoring well network, as they will influence the correct placement of the monitoring wells.

4.1-3.2.1 Aqueous Dissolved Phase Liquids (ADPLs)

Dissolved phase solutes, both inorganic and organic, move with the ground water, though their rate of travel may be different due to sorption, desorption, and degradation during transport. Dissolved phase solutes include miscible compounds such as methanol, ethanol, acetone and salts; partially miscible compounds such as Methyl Ethyl Ketone (MEK); and somewhat soluble compounds such as benzene. The solubility of metals varies widely and are greatly affected by the ground water chemistry. Essentially, all inorganic and organic compounds are soluble to some degree and may be found in the dissolved phase. The presence of the contaminant in the dissolved phase will not significantly affect the density of the water unless the concentration is in the range of 10^4 or 10^5 ppm.

4.1-3.2.2 Non-Aqueous Phase Liquids (NAPLs).

(a) "Floaters"

Those contaminants with a specific gravity of less than 1 will float on top of the water table aquifer as a separate, non-aqueous phase. Gasoline and the components of gasoline: benzene, toluene, and xylene (BTX) are usually considered "floaters." Gasoline spills often move erratically through the unsaturated zone and when they reach the water table the floating contaminant will flow downgradient on top of the water table. If monitoring wells are screened below the water table, it is possible that a floating phase may not be detected. Diagrams of floating product are shown on Figure 4.1-3.

(b) "Sinkers"

Non-aqueous contaminants with a specific gravity greater than 1.0 will tend to sink in an aquifer as a separate liquid phase. Some of the common "sinkers" are trichloroethylene (TCE), tetrachloroethylene (PCE), and other chlorinated hydrocarbons. Recent work by John Cherry of the Institute for Groundwater Research at the University of Waterloo in Canada has shown that many ground water contaminant investigations are not spending enough time searching for "Dense Non-Aqueous Phase Liquids" (DNAPLs).

Experiments described by Friedrich Schwille (1988) of West Germany suggest that, if there is an excess build-up of product above the water table, DNAPLs may sink rapidly in a water-saturated medium. Under the right circumstances, DNAPLs can continue to sink until they reach a relatively impermeable zone, where they begin to accumulate and migrate laterally. This impermeable zone may be a clay or silt layer or bedrock. When the DNAPLs reach this low permeability interface they tend to form bulbous mounds and flow downslope under the influence of gravity, independent of the direction of ground water flow. Figures 4.1-4 and 4.1-5 illustrate the migration of DNAPLs in porous media and fractured rock, respectively.

4.1-3.3 Preliminary Exposure Characterization

In contamination investigations, a preliminary exposure assessment must be undertaken to determine the receptors that may be impacted by the contamination. The identification of any potential human and environmental receptors is required in the initial stages of a preliminary assessment as outlined in the Massachusetts Contingency Plan (MCP) in section 310 CMR 40.543. Monitoring wells are frequently installed during and after the exposure characterization to determine the direction of ground water flow, its rate of migration, contaminant concentrations, and receptors subject to the highest risk.

4.1-4 METHODOLOGY

Designing a monitoring well network involves synthesizing information about the site geology, hydrology, ground water and contaminant chemistry, and human activities affecting the area being investigated. Monitoring well network design requires that the following steps be carried out:

- Compilation of available background data.
- Determination of the number and location of the wells and the vertical placement of the screened interval.
- Determination of the most suitable well type, size and construction materials.

Many innovative drilling and well installation techniques have been developed over the past few years as a result of the large number of site investigations being undertaken. Well installation technology is continually improving. One of the best resources for deciding on the feasibility of a specific well design is an experienced drilling contractor.

Often an experienced contractor can make helpful suggestions on modifications to a design that will improve the quality of well installation.

4.1-4.1 Compilation of Available Background Data

Prior to designing a monitoring well network all pertinent available information should be compiled and reviewed to understand the potential sources of contamination, the characteristics of all potential contaminants, and the geologic and hydrogeologic characteristics of the site. This background data may range from a limited quantity of published information about regional geology to detailed reports from previous phases of a site investigation. Typical sources of basic information include:

- Topographic maps.
- Previous investigative reports.
- United States Geological Survey (USGS) studies and reports.
- Graduate theses from local colleges and universities.
- Local well drillers.

- Soil maps published by the U.S. Soil Conservation Service.

Additional site-specific information should be compiled if available. This detailed record search may provide additional data on the site history, the nature of any contaminants at the site, man-made features that might affect ground water movement or contaminant migration, potential location of contaminant sources, and detailed information on site geology. For a more comprehensive discussion of the available resources see Section 2.1, Reconnaissance Investigations. This information might include any or all of the following:

- Recent and historical aerial photos.
- Previous engineering, geotechnical and hydrologic reports.

- o Regulatory files:

  - Local: Board of Health records; Conservation Commission files; Fire Department records of underground tank installations; insurance maps; assessor's maps

  - State: Department of Environmental Protection (DEP); Department of Public Health (DPH); Mass. Water Resources Authority (MWRA); Department of Public Works (DPW)

  - Federal: Environmental Protection Agency (EPA)

- o Insurance maps.
- o Company inventory files.
- o Interviews with owners/employees/operators.

4.1-4.2 Well Locations

Choosing well locations can be a difficult task. The best-laid plans in the office can fall apart once unforeseen field conditions arise. The key to designing a well network lies in the development of a "conceptual model" and the ability to refine that model as field information becomes available. Subsurface investigations can be compared to drilling through the roof of a house and trying to determine where one is and the number of rooms and floors. If one has a conceptual model(s) to work with (i.e. ranch, colonial or triple-decker) the number of wells can often be kept to a minimum.

4.1-4.2.1 Horizontal Spacing

The horizontal spacing of monitoring wells can only be determined on a site-specific basis. The size of the site, scale of the problem, the site layout, contaminant sources, geologic and hydrogeologic conditions, and potential receptors are all factors to be considered when deciding on the horizontal spacing of the wells. In general, the more complex the site conditions, the closer the spacing should be between wells.

In contamination investigations the horizontal spacing will ultimately define the areal extent of the plume by means of contaminated and uncontaminated wells. A combination of possible sources and the characteristics of site-specific contamination, along with the hydrogeologic conditions of the site (i.e. conceptual model), will indicate areas where contamination is most likely to be found.

Monitoring wells can be grouped into two categories: upgradient and downgradient.

(a) Upgradient Wells

The purpose of an upgradient well is to establish background ground water quality conditions within the aquifer. Upgradient wells should be screened at an interval which is hydraulically higher than, and which intersects the ground water flow path passing through, the point or zone within the aquifer of concern. Conditions may exist, either geologic or man-made, which make it impossible to install a well directly upgradient of a suspected source. For example, the source may be located adjacent to a local ground water divide or to a building. Such cases may require upgradient wells to be located hydraulically higher than, but laterally crossgradient from, the source area. This situation usually requires the installation of more than one upgradient well. Property lines do not qualify as a man-made condition unless access has been requested and refused.

In addition, an upgradient well must be located at a point unaffected by contamination migrating from the suspected source. To insure that this criterion is met, consideration must be given to effects such as ground water mounding and migration pathways within the unsaturated zone (i.e., perched zones, high hydraulic conductivity layers, etc.).

If more than one zone within an aquifer or more than one aquifer is contaminated, then the number of upgradient wells must be adequate to monitor each stratigraphic zone. In the course of an investigation, it may be found that the upgradient well of one source becomes the downgradient well for another. If more than one source exists, it will be necessary to install several upgradient wells. Ultimately one must be confident that the location of the background well(s) is upgradient of the source or area of concern.

(b) Downgradient Wells

Downgradient wells, as the name implies, are located hydraulically "downgradient" with respect to a particular point, area, or zone within an aquifer. They are located in the "down" or lower direction with respect to the slope of the potentiometric surface. "Down" also is more clearly shown on cross-sections showing the potentiometric water surface. Downgradient wells should be placed in areas where the ground water flows through and from a source of contamination. In contaminant investigations, downgradient wells are used to define the extent of the plume and to track its migration. The three-dimensional nature of ground water flow requires a sufficient number of wells be located within and outside a plume of contamination to define it both vertically and horizontally. A review of the hydrogeologic conditions observed in the field, in addition to field screening and visual observations of soil, may provide useful information in developing a conceptual model to help select downgradient well locations. Zones and areas of preferential flow (i.e., strata with relatively high hydraulic conductivity, fractures, faults, solution channels, utility trenches, and underdrains) should be monitored. Again, it is important that the monitoring well be screened in the same stratigraphic zone(s) or flow path(s) where contamination is suspected or has been detected.

4.1-4.2.2 Vertical Spacing

The depth and screened interval of monitoring wells is just as important as the horizontal spacing. In some situations (i.e., recharge and discharges zones) vertical gradients may be more pronounced than horizontal gradients and may exert the most significant influence on dissolved contaminant movement. The determination of vertical gradients requires the installation of multi-level wells with short screen lengths. If the bedrock is highly fractured, it may be appropriate to install wells in the bedrock to determine the direction of ground water flow between the rock and overlying unconsolidated deposits. The nature of the contaminants themselves should be considered to determine the vertical placement of screened intervals. For example, if the contaminants of concern are "floaters" it would be appropriate to monitor the upper zone of the aquifer across the water table. Where the contaminants are "sinkers," and a release of product is suspected, well clusters or multi-level systems may be required to determine the specific depth of contamination within the aquifer. Well screens may be placed at or slightly above an impervious boundary such as a till or bedrock interface to look for pooling of "sinking" contaminants. In practice this is extremely difficult to do because of the irregularities of these interfaces. Often the presence of a DNAPL is inferred by comparing the solubility of the contaminant with its dissolved concentration in the ground water. Dissolved values of 20% to 40% of the solubility may indicate the presence of a DNAPL pool. The importance of placing the screened interval in the appropriate stratigraphic zone(s) has already been emphasized in the section on horizontal spacing.

4.1-4.3 Selection of Well Type

Once the site characteristics are understood, well types can be selected based on the intended application and the duration of the monitoring program. A discussion of the various types of wells installed in site investigations is presented below. In addition to the type of well, several other factors must be considered. These include drilling methods, subsurface sampling techniques, well construction materials, installation procedures, casing materials, filter packs, seals, security, and sampling methods. Procedures for selecting well construction materials and methods of installing wells are discussed in Sections 4.2 and 4.3, respectively.

There are several types of wells that may be installed. For the purposes of this section the wells will be described as piezometers, observation wells, and monitoring wells. Figure 4.1-6 illustrates various well types.

The selection of the type of well to be installed should be based on the purpose of the well (i.e., water level measurements, permeability testing, or ground water quality sampling).

4.1-4.3.1 Piezometers

A piezometer is a well with a short screen length isolated in a specific zone within an aquifer; it measures the average potentiometric head over the short length of the screen. They may be drilled or driven to the desired depth and may or may not have divider seals at the top of the screen. Driven piezometers should not be used if there is a concern for cross contamination at the site. Piezometers usually have small diameters and are not designed for the collection of quantitative ground water samples. Piezometers should be installed when the purpose is limited to obtaining water level measurements and/or obtaining qualitative ground water quality data. Piezometers are effective at all stages of a site investigation to characterize ground water flow conditions and to determine horizontal and vertical hydraulic gradients. They are especially useful in the initial stages where characterizing the aquifer conditions will allow more accurate placement of monitoring wells. A piezometer can be constructed of small diameter (generally 3/4-inch to 1.5-inch I.D.) metal or PVC pipe having a terminus that is open, a screened well point, or a porous ceramic tip. Piezometer clusters provide useful information about horizontal and vertical hydraulic heads.

- Advantages

  Lower cost for installation than the larger diameter monitoring wells.

- Disadvantages

  Generally not designed to allow for ground water (environmental) sampling. The diameter of the well is too small to allow some sampling tools to be used.

4.1-4.3.2 Observation Wells

The term observation well refers to a small diameter well with a long screen designed and installed to measure the average water level; it is not designed or constructed for sampling purposes. Observation wells are appropriate for installation in the saturated zone when the primary purpose is to obtain water level information. They should not be used at contaminated sites where water quality samples will be needed. The term observation well is often associated with wells installed and/or used during pump tests to monitor the aquifer's response to pumping.

- o Advantages

  Relatively inexpensive method to obtaining general information about aquifer characteristics such as depth to the water table, in-situ permeability testing, and the aquifer's response to pumping.

- o Disadvantages

If there are large vertical gradients within the saturated zone an observation well will yield average conditions, potentially resulting in erroneous readings and a misinterpretation of the potentiometric conditions. Not suitable for quantitative chemical ground water sampling.

4.1-4.3.3 Monitoring Wells

The term monitoring well is used to describe a large diameter (a recommended minimum of 2.0 inch ID or larger) well which is used for obtaining representative samples of the ground water, water-level data, and conducting in-situ permeability tests. In selecting the most appropriate monitoring program, one must decide whether a single well or a multi-level well is appropriate. Because ground water problems are three-dimensional, it is always necessary to have some multi-level wells to define the top and the bottom of the zone of contamination. The factors determining the type of well to be selected include the site geology and hydrogeology, contaminant characteristics, well casing material, and the number, location and design of any existing monitoring wells.

(a) Single Standpipe Wells

Single monitoring wells should be selected when the purpose is to monitor one specific zone within an aquifer (depth specific) or to monitor a large area within an aquifer (depth integrated).

(1) Depth-specific Wells A depth-specific monitoring well uses a short screen length (not longer than 5 to 10 feet) to monitor a distinct zone within the aquifer. For instance, if the objective is to detect and sample contaminants that are less dense than water, a single well with screen straddling the water table would be appropriate. Situations where single wells are sufficient are:

- o Thin saturated thickness of upper aquifer.
- o Homogeneous geology in upper aquifer.
- o Monitoring for single or similar type of contaminants.

- o Where no vertical zones gradients have been found to be present.

- o <u>Advantages</u>

  Allows determination of actual contaminant concentrations at a specific depth in an aquifer.

- o <u>Disadvantages</u>

Monitoring at a discrete level may not detect contamination at a different level within an aquifer.

(2) <u>Depth-integrated Wells</u> A depth-integrated monitoring well uses a long screen length (>10 feet) to monitor a larger portion of an aquifer. Site conditions dictate where this type of well would be appropriate:

- o Aquifers with relatively low permeability.

- o Aquifers with widely fluctuating water tables.
- o Situations where separate phase liquids are not being monitored.

- o <u>Advantages</u>

  Enables sufficient flow of water into a well to allow for sampling in aquifers with low permeability.

  Enables sampling for contaminants that are less dense than water in aquifers with widely fluctuating water tables.

- o <u>Disadvantages</u>

  Longer screened zones may dilute samples by allowing large volumes of uncontaminated water to mix with relatively small zones of contamination. This could result in lowering the concentration of contamination detected, effectively diluting the sample to concentrations below laboratory detection limits.

  There is a potential for migration of contamination from one depth to another via the long well screen.

  Due to the disadvantages inherent in depth-integrated wells, DEP generally does not recommend their use except during the exploratory or preliminary phase of a hydrogeologic investigation at a contaminated site.

(b) <u>Multi-level Wells</u>

Multi-level monitoring wells should be installed when the purpose is to monitor more than one level within an aquifer, more than one aquifer or multiple bedrock fracture zones. They are useful in delineating the vertical distribution of contamination within a single aquifer, as well as providing information on vertical head gradients. Included in this category are stacked or nested wells, well clusters, and specialized well systems such as Waterloo, Westbay and Barcad wells.

(1) <u>Stacked Wells (Well Nest)</u> A stacked or nested well consists of several piezometers or monitoring wells installed in a single borehole. The screens are set at different depths and are separated by seals.

- <u>Advantages</u>

  Economical - only one borehole is necessary for several wells

- <u>Disadvantages</u>

  The major problem with this type of system is the questionable integrity of the seals between screened intervals. As the number of standpipes per borehole increases it becomes increasingly difficult to effectively seal off the previously placed screens. The result may be migration of ground water contamination from one zone to another zone.

  The integrity of the seals should be tested by pumping one well at the nest and looking for no effect in the other well(s) of that nest.

  Well installation is difficult due to the limited annular space between the borehole wall and the standpipes. Bridging of sand pack and/or bentonite seals may occur.

(2) <u>Well Cluster</u> A well cluster or multiple set is a group of single wells, each installed at different levels in separate boreholes. Compared to the stacked well system this system more effectively seals the wells at discrete zones within the aquifer. The effectiveness of this monitoring system depends on the integrity of the annular seals.

- <u>Advantages</u>

  Allows for monitoring of several vertical zones within the saturated thickness while maintaining the integrity of discrete zones

  Allows for determinations of potentiometric water levels at discrete depths (vertical gradients)

- <u>Disadvantages</u>

Increases the amount of drilling and well installation time and consequently these systems become more costly to install.

(3) Specialized Well Systems: Waterloo, Westbay, and Barcad. Specialized well systems, such as the Waterloo, Westbay and Barcad systems, consist of multi-level monitoring wells installed in a single borehole. They can be installed in both unconsolidated or bedrock aquifers. The Waterloo and Westbay system are constructed with specially designed seals or packers that, if installed properly and under the right conditions, provide an effective seal between zones in a borehole. Following is a brief description of each type of system:

- Waterloo

  The Waterloo monitoring system consists of a bundle of dedicated small diameter sampling tubes that are installed at various depths in the borehole through a common standpipe (see Figure 4.1-7). The tubes are open at the bottom and each zone is sealed by a water-activated material that forms the packer. Ground water samples are collected with a gas-driven sampling device.

- Westbay

  The Westbay well system consists of a multi-port system attached to a central standpipe. Each monitoring zone is separated by a packer. The packers are inflated by injecting them with water. The actual monitoring zone consists of the annular space between the borehole wall and the central standpipe in between packers (Figure 4.1-8). Specialized tools are required to measure water levels and sample Westbay wells.

- Barcad Systems

  The Barcad system utilizes gas driven samplers and tubes positioned at selected depths in a single borehole (Figure 4.1-9). The samplers are connected to the surface by a gas drive tube through which a sample is collected (Figure 4.1-10). The samplers are isolated by bentonite seals. Although the system is similar to the stacked standpipe system, the relatively small diameter tubes allow a more effective seal to be installed between monitoring zones.

- Advantages

  Allows for installation of a multi-level well in a single borehole; minimizing drilling and well installation time and costs.

  Allows for determination of potentiometric levels at discrete depths within aquifer

  Smaller inside diameters reduce the need for purging large volumes of water prior to sampling

- <u>Disadvantages</u>

  In most cases systems require specialized equipment and a trained field technician for sampling.

  Packers on the Waterloo system are self inflating (water-activated). May be a problem when installing in deep (greater than 300 feet) boreholes.

  Small tubes in the Barcad- and Waterloo-type systems may become damaged or crimped during installation. Also, water levels may be difficult to measure due to the small diameter of the tubing.

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MONITORING WELL NETWORK DESIGN

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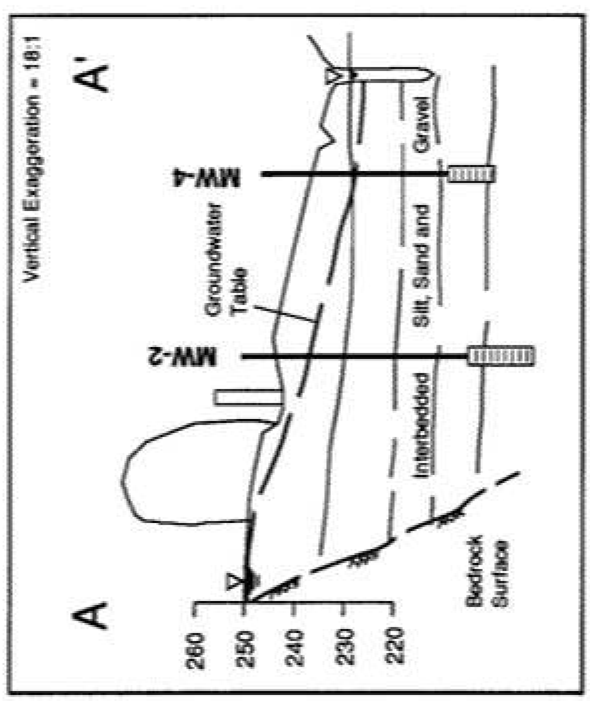


Figure 4.1-1

Conceptual Geologic Cross Section.

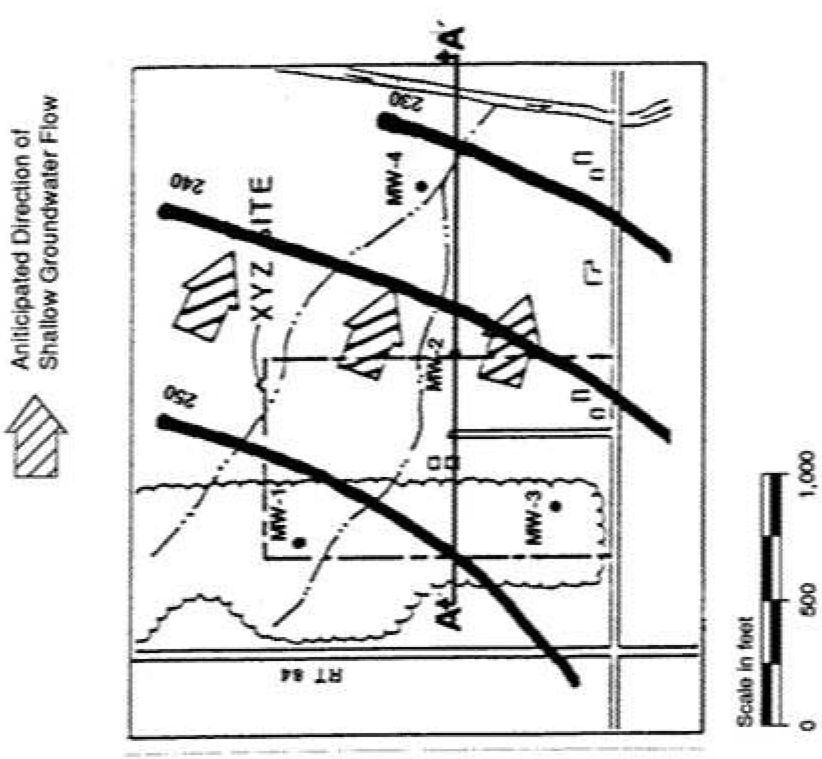
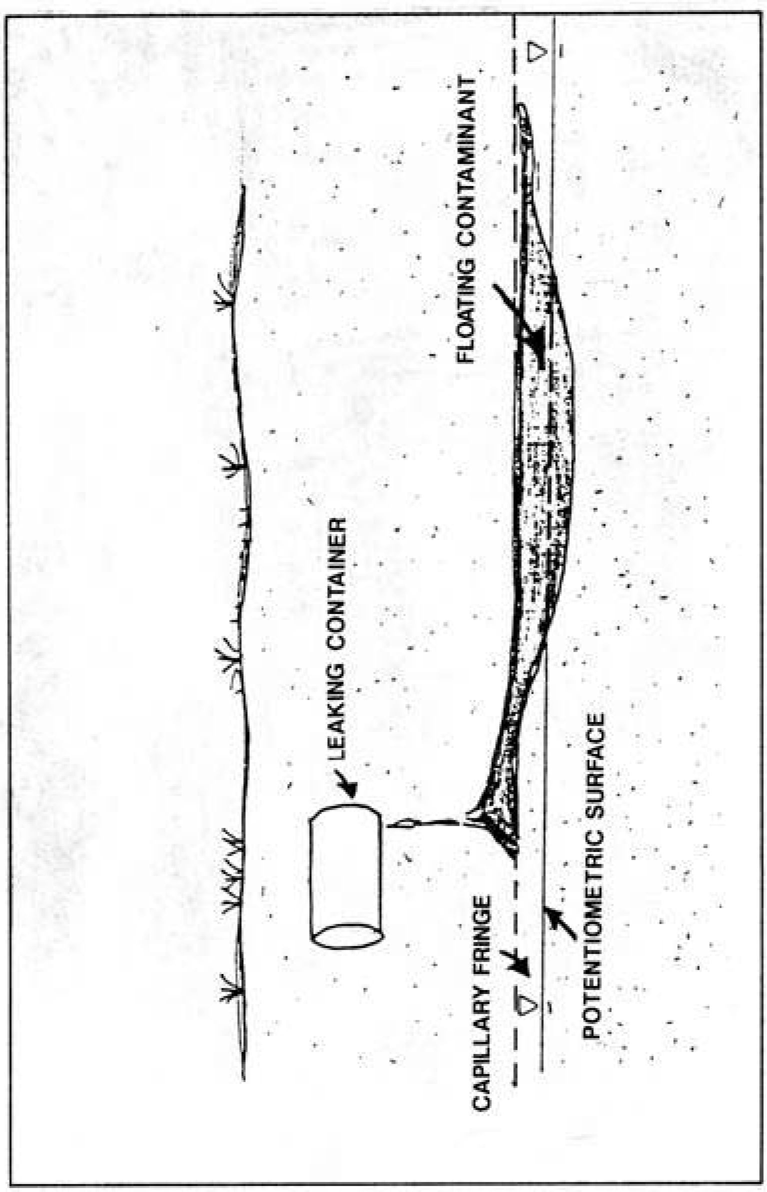


Figure 4.1-2

Conceptual Groundwater Contour Map.

Source: MADEP



Source: MADEP

Figure4.1-3

Sketch of Floating Contaminant.

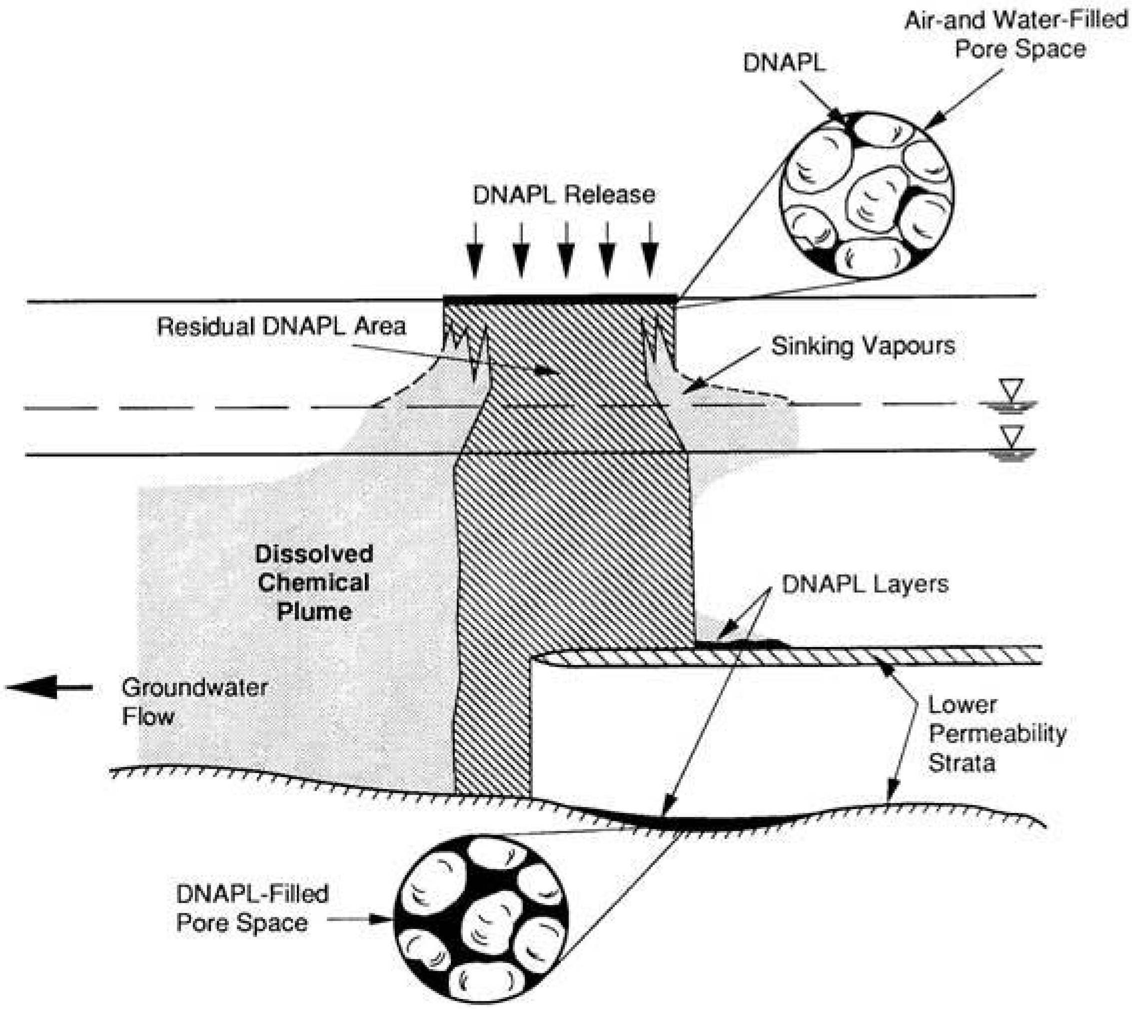


Figure 4.1-4

Illustration of Sinking Contamination in a Porous Material.

Source: After Cherry (1988)

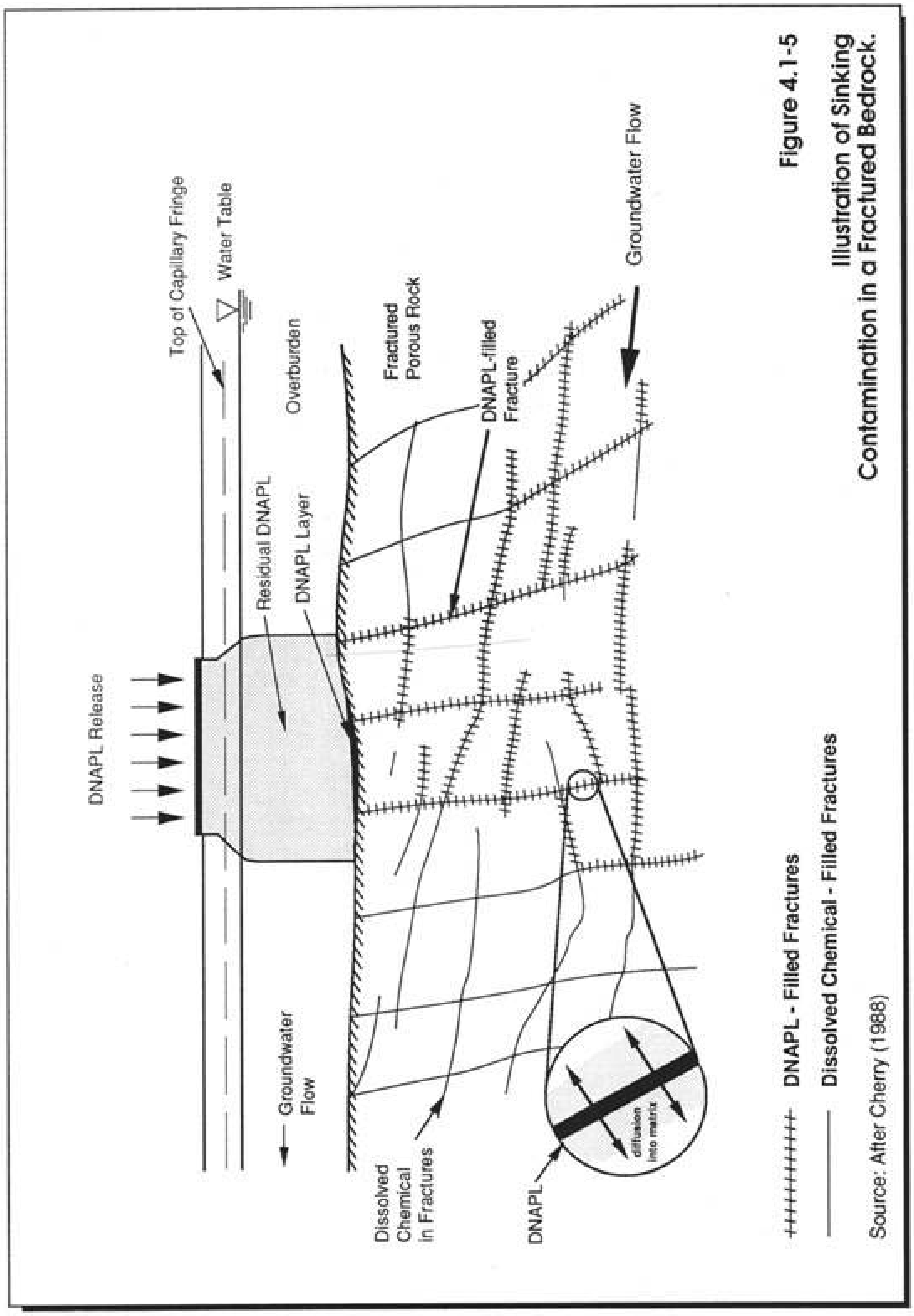


Figure 4.1-5

Illustration of Sinking Contamination in a Fractured Bedrock.

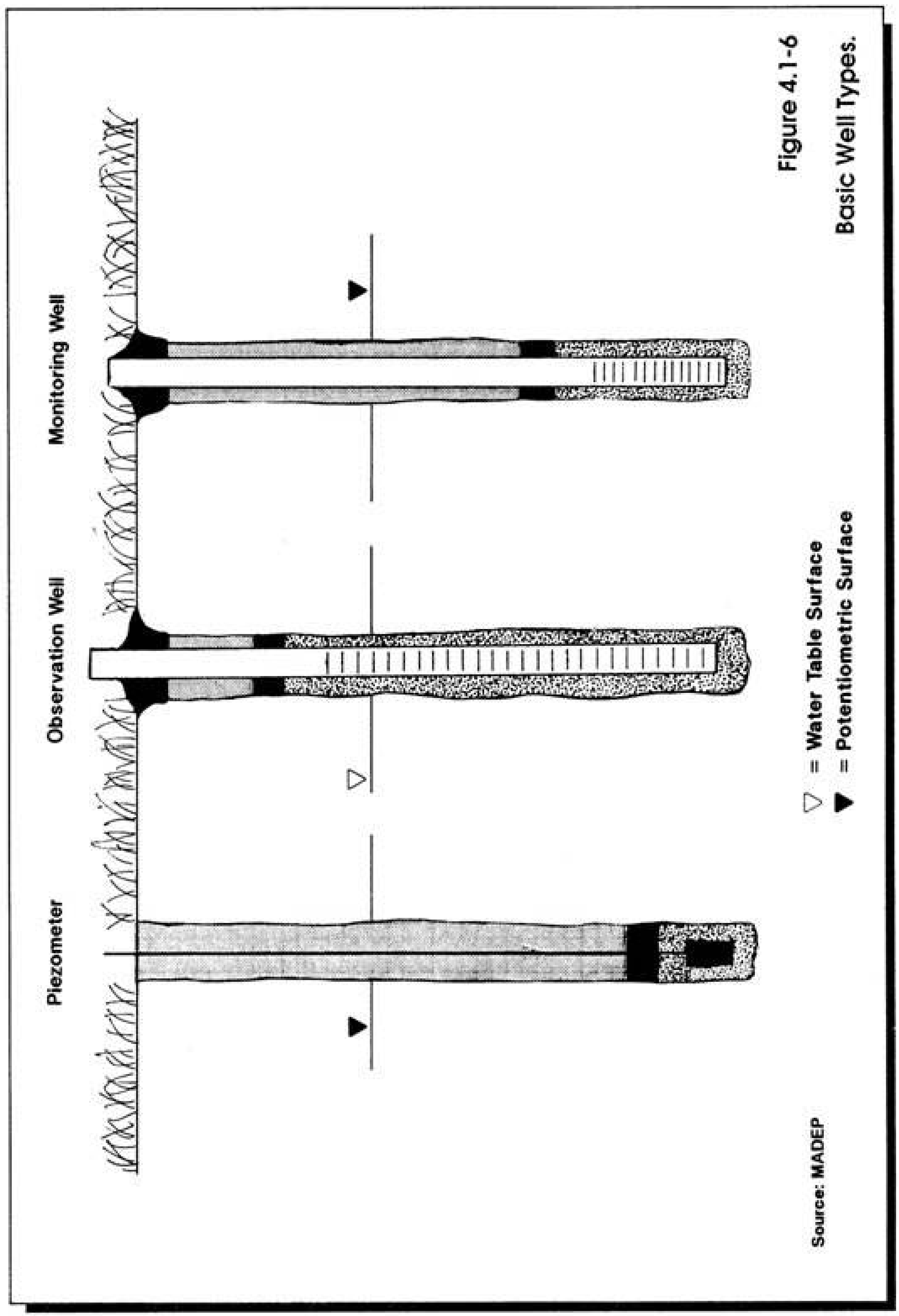


Figure 4.1-6
Basic Well Types.

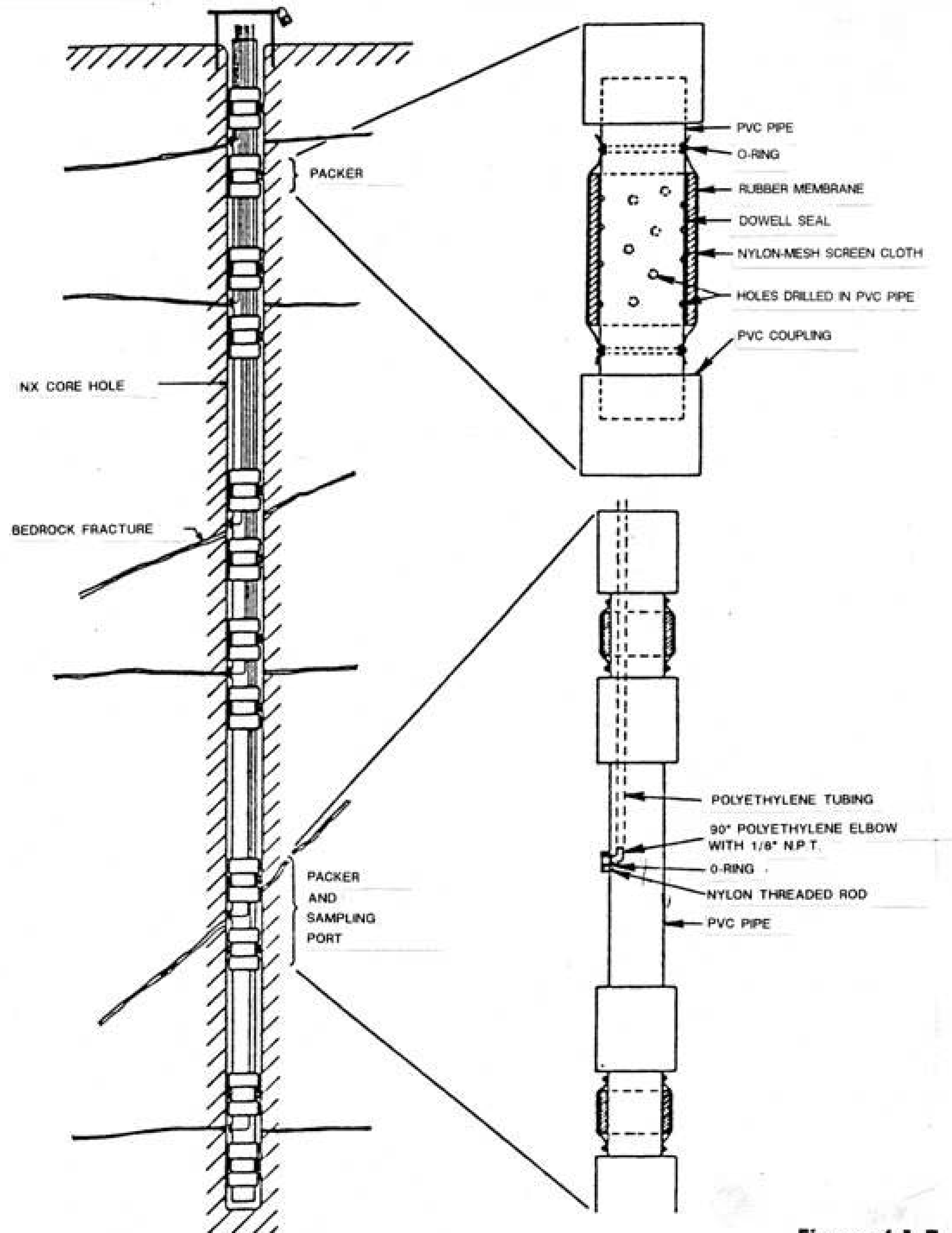


Figure 4.1-7

Source: Solinst Canada Ltd.

Waterloo Multilevel Monitoring Well Detail.

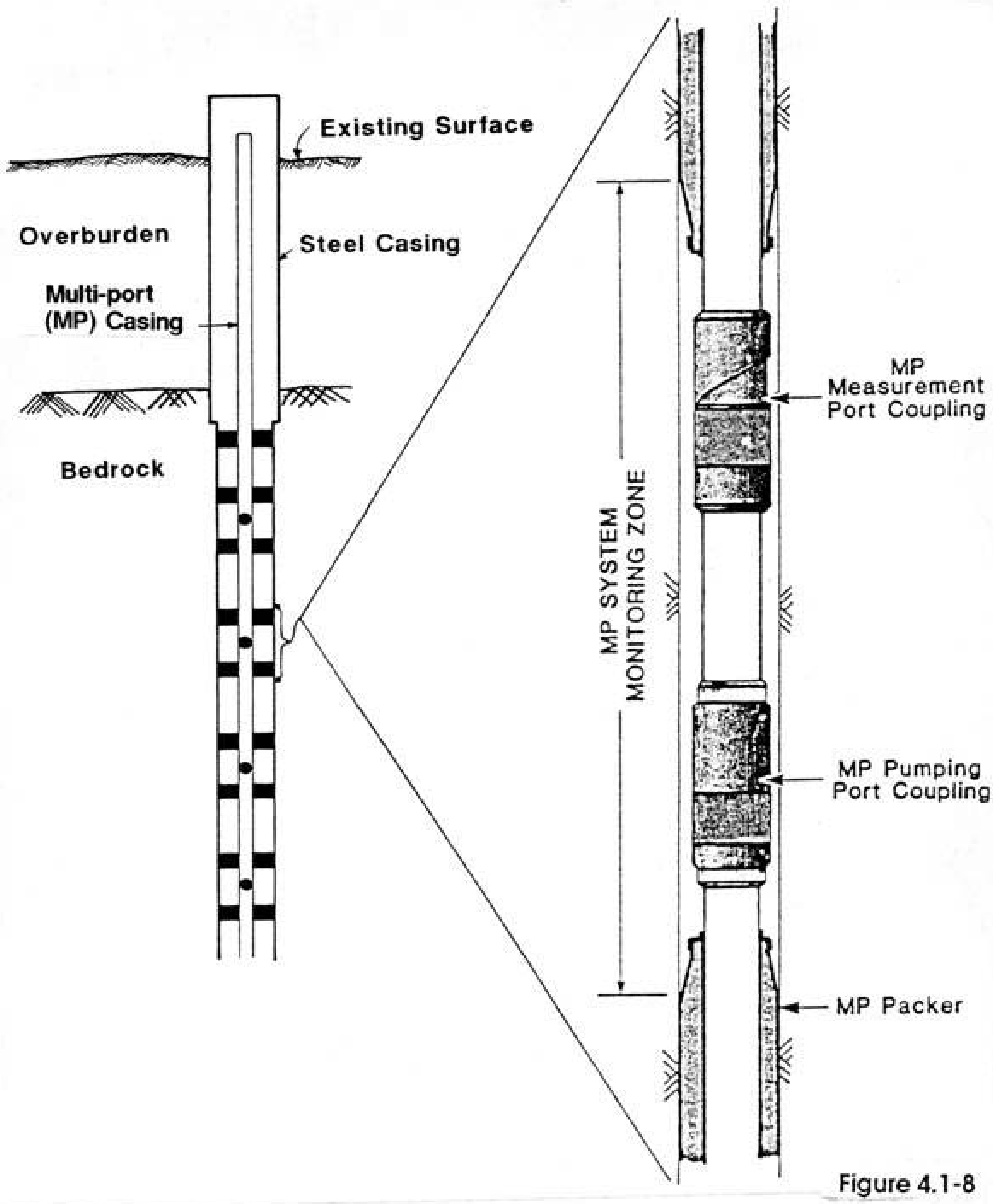


Figure 4.1-8

Source: Westbay Instruments Inc.

Westbay Multilevel Well.

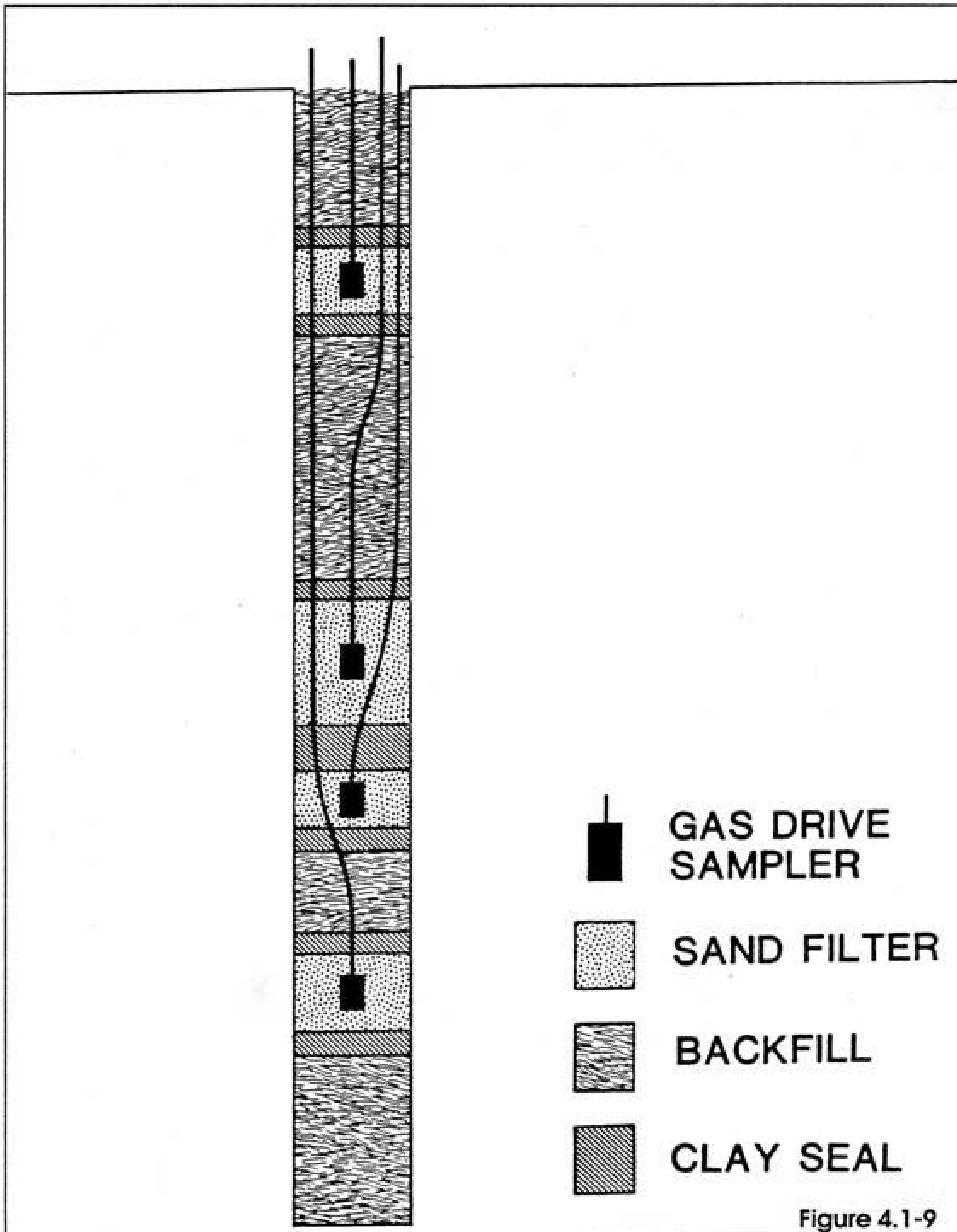


Figure 4.1-9

Typical Barcad Installation.

Source: MADEP

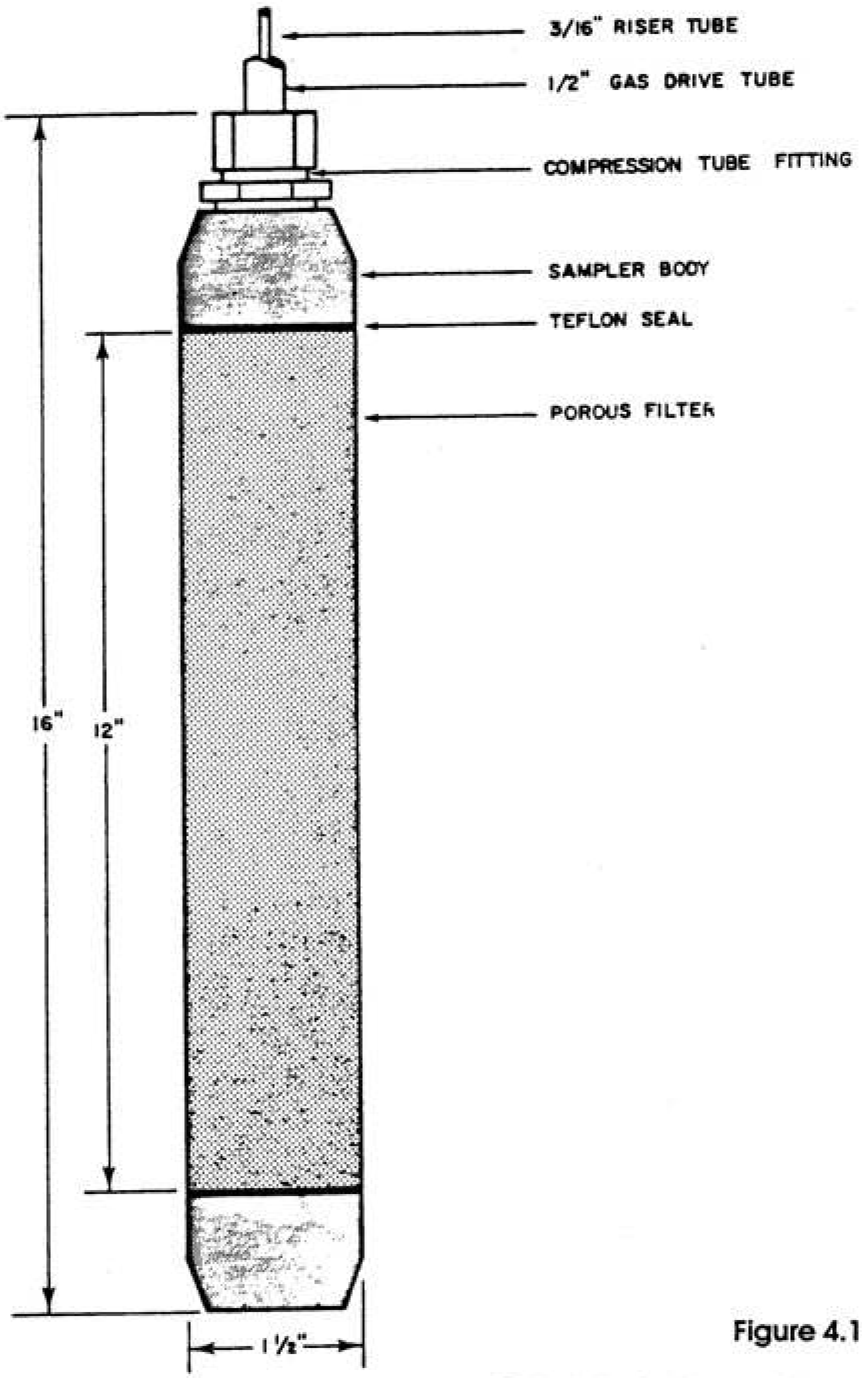


Figure 4.1-10

Detail of a Barcad Sampler.

Source: Barvenik and Cadwgan (1980)

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 4.2 SELECTION OF WELL CONSTRUCTION MATERIALS

SECTION 4.2
SELECTION OF WELL CONSTRUCTION MATERIALS

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SECTION 4.2
SELECTION OF WELL CONSTRUCTION MATERIALS

4.2-1 PURPOSE

The purpose of this Standard Reference (SR) is to provide guidance for selecting the most economical and chemically inert monitoring well construction materials. While there are many similarities with the process of selecting materials for water wells, there are also major differences that may be significant, especially in a highly contaminated environment. Monitoring well casing and well construction materials should be selected to meet the following criteria:

- o The materials should be resistant to deterioration resulting from long-term exposure to natural or synthetic chemical constituents in the ground water at the site.

- o The materials must have sufficient strength to ensure the structural integrity of the well during installation and long-term monitoring.

- o The materials should be selected to minimize their interference with the measurement of specific chemical parameters expected to be found at a site.

- o The casing diameter should be large enough to accommodate commercially available down-hole instrumentation or sampling equipment (e.g., oil/water interface probe), but also small enough to minimize the volume of water to be purged from the well.

- o The well casing should be watertight.

- o The well must be able to be secured against vandalism, leakage, and inadvertent damage.

- o The screen and filter pack must be appropriately sized to provide representative data on hydraulic conductivity and ground water quality.

This section provides guidance for the selection of materials commonly used in monitoring well installations, and discusses the advantages and disadvantages of each. Figure 4.2-1 depicts the basic materials comprising a monitoring well: casing or riser, screen, filter pack, seals, and protective casing. The selection of well construction materials should be site-specific. Proper selection requires consideration of the project objectives, compliance with regulatory requirements, available data about the site geology, water chemistry, and the project budget. Section 4.1 Network Design describes important considerations for designing a good monitoring well. Well installation procedures are discussed in Section 4.3, and Section 4.4 discusses the minimum requirements for As-built Notes and Records of monitoring wells. New well materials, filter packs and sealants are continually being developed. Individuals involved in well design and installation should be aware of recent developments in monitoring well technology.

Ground Water Monitoring Review, a quarterly publication of the National Water Well Association, is a useful source of innovative and improved monitoring techniques. Another valuable source of information on the availability and feasibility of using various well materials is a drilling contractor experienced in monitoring well installation. Experienced drilling contractors are capable of providing insight into the compatibility of various well construction materials with a particular drilling technique, as well as information on the amount of time an installation may require, and potential problems that particular materials may present during installation.

4.2-2 CASING MATERIALS

The casing, or riser, is the part of the well that extends from the top of the well screen to the ground surface (see Figure 4.2-1). When selecting well casing and screens, both the composition and diameter must be taken into consideration.

4.2-2.1 Composition

There are a number of commercially available well casing materials. The advantages and disadvantages of only a few of the most commonly used materials are described below. It is possible to combine different materials as long as they are compatible. There is considerable debate over the significance of the adsorption and desorption potential of many well casing materials. However, adequate purging of the well prior to sampling reduces or eliminates the potential for this to have a significant impact on sample chemistry. If in doubt about the suitability of a particular casing for a ground water problem, it is advisable to consult chemical compatibility charts or the manufacturer for additional information. The significance of the adsorption-desorption problem must be evaluated based on the monitoring well program objectives, sampling and analytical requirements, and the concentrations one is trying to measure.

4.2-2.1.1 Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) is the most common well casing material used in monitoring well construction. PVC is thermoplastically molded casing composed of a rigid, unplasticized polymer. PVC casing offers a combination of chemical resistance, durability, availability, and low cost. There is considerable debate over the reaction of PVC well casing with some ketones, aldehydes, and chlorinated solvents. In some cases, PVC has been shown to adsorb and desorb low levels of organic compounds.

Flush-threaded or coupled PVC casing should be used for monitoring well construction. If flush-threaded casing is used, ASTM specified thread specifications should be used. Under NO circumstances should solvent cement be used to join casing sections together. PVC solvent cements have been shown to contribute significant quantities of organic contaminants to water samples collected from cemented PVC wells. Generally, flush-threaded casing is preferred due to the ease of installation and because, if properly joined, it provides a water-tight seal.

For all monitoring well applications where PVC is selected, only PVC well casing listed with the National Sanitation Foundation (NSF) should be used. These products are essentially free of readily leachable plasticizers and do not exceed the National Interim Primary Drinking Water Standards in leach tests.

Advantages

- Excellent chemical resistance to weak alkalis, alcohols, aliphatic hydrocarbons, and oil and grease.
- Good chemical resistance to strong mineral acids, strong oxidizing acids, and strong alkalis.
- Readily available.
- Lightweight.
- Inexpensive.
- Two wall thicknesses commonly available (Schedule 40 and 80) provide a choice of strengths.

Disadvantages

- May adsorb and desorb low levels of some organic constituents from the ground water. This may not be a problem if the well is adequately purged prior to sampling.
- Poor chemical resistance to concentrated ketones, esters, and some aromatic hydrocarbons.
- Weaker, less rigid, and more temperature-sensitive than metallic casing materials.

4.2-2.1.2 Stainless Steel

Stainless steel provides an excellent casing material where corrosion resistance and strength are important. The strength provided by stainless steel may be essential when installing wells in deep boreholes (over 300 feet deep) due to the potential for other casing materials with lower strengths to collapse. Stainless steel is resistant to most chemicals and is suitable for monitoring many types of contaminants. Long periods of exposure to highly corrosive ground water conditions may result in leaching of chromium or nickel from stainless steel well casing. Therefore, if the pH of the ground water is low (4 or less), stainless steel is not recommended for long-term monitoring of inorganic constituents. Stainless steel is available in a variety of types, each with a slightly different composition. The basic composition and suggested applications for various types of stainless steel and other metals for well casing and screens is presented in Table 4.2-1. As with PVC, stainless steel casing should have threaded, flush joints to assure watertight connections.

Advantages

- Excellent resistance to corrosion and oxidation; will not adsorb or desorb organic contaminants.

- High strength, rigidity.

- Suitable for wide range of temperatures.

- Readily available.

Disadvantages

- Susceptible to galvanic and electrochemical corrosion.
- Heavy; may require additional equipment to lower down borehole.
- May leach chromium and/or nickel in acidic waters.
- Moderate to high cost.

4.2-2.1.3 Teflon

Teflon is a fluorocarbon polymer developed by Dupont. Teflon displays a high resistance to chemical attack, reportedly low adsorption of chemicals, and low leaching of the casing compounds. Most Teflon materials available for monitoring well applications have been manufactured specifically for ground water monitoring applications.

Advantages

- High resistance to chemical attack.
- Very limited adsorption capacity.
- Low potential for leaching.
- Lightweight.

Disadvantages

- Low tensile strength and rigidity.
- Tendency towards excessive slippage during installation.
- Limited availability.
- In deep installations slots in screen may close under the weight of the riser.
- Comparatively high cost.

4.2-2.2 Size

The size of the well casing, both the wall thickness and the inside diameter (ID) of the pipe, is a consideration when selecting well construction materials. The wall thickness determines the strength of the casing material, and the inside diameter must provide enough room for downhole instrumentation. The thicker the casing, the stronger the pipe. Pipe or casing thickness is described in various "schedules." For PVC monitoring well applications, Schedule 40 and Schedule 80 are commonly used. Schedule 80 is thicker and stronger than Schedule 40. Metal casing materials also come in various wall thickness, or schedules.

Monitoring well casing materials are available in 3/4-, 1-1/2-, 2-, 4- and 6-inch ID sizes. With the exception of specialized installations such as Barcads, Westbay, and others, a minimum inside diameter of 2 inches is recommended by DEP for all standard monitoring well installations. This minimum diameter does not apply to piezometers, which are only to be used for water-level measurements or qualitative sample analysis. Two-inch ID wells will accommodate most commercially available sampling pumps, bailers, and transducers. In some applications larger diameter wells may be desirable so that standard pumps and skimmer systems can be used. It should be noted that large diameter wells (4-inch and greater) may require substantially longer purging time before a sample can be collected and will produce large volumes of purge water. The volume per linear foot of casing is directly proportional to the square of the casing diameter. Table 4.2-2 shows the volume of water contained in casings or holes of various diameters.

The selection of the size of the well casing will also influence the size of the borehole needed for proper installation of the well screen and casing, and the quantity of filter pack and seal needed. As described in Section 4.3 Installation of Wells, ideally the diameter of the borehole should be at least 4 inches greater than the outside diameter of the well screen and the riser pipe.

4.2-3 WELL SCREEN SELECTION

A well screen is a filtering device that serves as the intake portion of wells constructed in unconsolidated or semiconsolidated aquifers. The screen provides a hydraulic connection to the saturated aquifer so that representative water level and chemical data can be obtained. It permits water to enter the well from the saturated aquifer, prevents sediments from entering the well, and serves to structurally support the unconsolidated aquifer material. The considerations of composition, resistance to corrosion, sufficient column and collapse strength, and inside diameter for well-screens are the same as for well casings; however, the strength of the screened section is less than that of the riser sections due to the openings. Additional screen criteria and functions that should be considered are slot size (i.e., percentage of open area) and style (i.e., non-clogging slots).

4.2-3.1 Slot-size

Well screens are categorized based on the width of the openings in thousandths of an inch. No. 10 slot, for example, represents an opening of 0.010 inch. Generally a 10-slot or 20-slot (0.010- or 0.020-inch, respectively) screen is appropriate for monitoring wells where low pumping rates are used. Obviously, it is important that the filter pack around the screens be larger than the screen slots to prevent infiltration of the pack during purging and sampling. Slot-size selection is also important if the well is to be used for field permeability tests in coarse-grained materials where a small slot size might have a lower hydraulic conductivity than the native soils. Also, in situations where highly viscous materials (i.e., heavy oils or creosote) are being monitored, a large slot size is preferred to avoid inhibiting flow through the screen. The spacing of the slots may be varied also, if desired.

4.2-3.2 Style

Two types of standard well screens are commercially available for monitoring well construction: slotted pipe and wire wound continuous slot (see Figure 4.2-2). Hand-cut or hand-slotted screens are not sufficiently uniform to produce a satisfactory well screen; they should never be used for monitoring wells.

4.2-3.2.1 Slotted Pipe

Slotted pipe consists of standard well casing that has been machine perforated with parallel rows of slots. The size, frequency and configuration of the slots will vary with the application and manufacturer. In general, slotted screens have approximately 5 to 10 percent open area. Table 4.2-3 shows the total slot area of screens of various gauges in square inches per foot.

Advantages

- Machine-manufactured - good slot size control.
- Readily available.
- Inexpensive.

Disadvantages

- Limited open area; this may inhibit efficient well development.
- Prone to clogging by fines.

4.2-3.2.2 Wire-wound, Continuous Slot Pipe

Wire-wound, continuous slot screens provide a larger open area than slotted screens, typically twice as much. Wire-wound screens consist of triangular-shaped, continuously wound wire connected by vertical bars. The V-shaped openings are wider on the inside than the outside, reducing the likelihood of clogging by formation materials.

Advantages

- Good slot control; wide range of sizes available.
- Larger percentage of open area than slotted screens.
- Large open area allows fluid to enter at a low velocity, reducing the turbidity of sample.
- Less susceptible than slotted pipe to plugging due to V-shaped slots.

Disadvantages

- More expensive than screens made of slotted pipe.

PVC-wound screen is commercially available and has the same advantages as the wire-wound screen. This product is not generally recommended because it is more expensive than the slotted PVC pipe and has a low collapse strength.

4.2-3.3 Sediment Sump

In formations of fine sand, silt, or clay it may be difficult to completely prevent the migration of fines through the filter pack and screen. Where suspended fines are a problem, the monitoring well can be constructed with a sediment sump below the screened zone to collect the fines. An example of a sediment sump is shown in Figure 4.2-3. If a sediment sump is employed, one must be careful that the accumulated fines are not disturbed and suspended during purging or sample collection. If a submersible pump is used, it should be placed a substantial distance above the sump to avoid becoming clogged by fines that have collected in the sump.

4.2-4 FILTER PACK

A filter pack around the screen helps to reduce the movement into the screen of fine-grained materials that could potentially clog the screen and inhibit water movement. In addition, the filter pack provides support around the well screen to prevent the formation materials from collapsing around the screen. An effective filter pack provides a zone of high hydraulic conductivity around the screen and reduces the infiltration of fines. The filter pack must be chemically inert; otherwise, it may affect the chemistry of the ground water as it passes through the pack and into the well.

When monitoring wells are installed in formations with a wide range of particle sizes, effective filtration can be difficult. Filter packing procedures recommended for water wells are not suitable for monitoring wells, unless the hydraulic characteristics of the formation materials are similar to those of an aquifer (i.e., thick deposits of coarse sand and fine to medium gravel). To exclude the entrance of fine silts, sands, and clays into a monitoring well, the grain-size distribution curve for the filter pack ideally is selected by multiplying the 50-percent retained size of the finest formation sample by 2. This approach may not be practical in fine-grained materials (i.e., silts and clays). This leads to a more conservatively sized filter pack than would be selected for a water supply well. Uniformity coefficients should range from 2 to 3 (Driscoll, 1986).

All filter pack material should be purchased from reputable suppliers who have properly cleaned and bagged the material. The importance of the cleanliness of the filter pack should be emphasized. Typically, washed sand or silica sand is used for filter packs around monitoring well screens. In some uniform, coarse-grained formations the native soil materials are allowed to collapse around the screen, providing a suitable, natural filter pack. According to Gass (1988), monitoring wells should be filter-packed under the following circumstances:

- When there is more than 10 to 15 percent clay-/or silt-sized particles in the formation.

- When the well is completed in a formation consisting of relatively fine uniform sand.

- When the physical characteristics of the formation in the screened zone are highly variable.

- When the formation is composed of friable or fractured rock, which allows sand, silt or clay to enter the well.

- When the formation is not an aquifer.

The amount of filter pack ordered should be sufficient to enable the filter pack to be as thick as practical, particularly in low permeability soils. Oversized borehole diameters are recommended for monitoring wells screened in silt and clay soils to accommodate a large volume of filter pack. Two types of filter packs are discussed below.

4.2-4.1 Washed Sand

Washed sand typically consists of concrete or mortar sand that has had only the fine particles removed by washing and screening. Washed sand is usually available in different size ranges. This material is generally available in bulk quantities. The quality assurance and control of this type of material should be reviewed. Lack of QA/QC is often a limiting factor for use as a monitoring well filter sand. A representative sample should be collected during drilling for analysis at a later date should concerns arise over the quality of the material.

Advantages

- o Inexpensive.
- o Wider range of grain sizes than silica sand
- o Readily available.

Disadvantages

- o Chemical composition and reaction with ground water usually not known.

- o In deep boreholes particle-size segregation may occur during free-fall installation. Proper installation may require emplacement with a tremie pipe.
- o Lack of QA/QC for this source.

4.2-4.2 Uniformly-graded Silica Sand

Uniformly graded silica sand is manufactured by crushing quartzite into small particles. It is manufactured for sandblasting and can be purchased in bags. It is available in a variety of grain-sizes, but it is usually more uniform in size than washed sand. Its angularity is greater than that found in most washed sands. Ottawa sand is a brand name for silica sand that comes from Ottawa, Illinois. Ottawa sand is more rounded and spherical than other silica sand products. It is frequently specified for monitoring well installations, but it is much more expensive than locally manufactured silica sand with the same specifications. These products generally have acceptable QA/QC for use as a filter sand for monitoring wells.

Advantages

- o Composition is essentially pure silica; as such, it is chemically inert.
- o Generally has acceptable QA/QC.

- o Readily available in bags.
- o Easy to install.

Disadvantages

- o More expensive than washed sand.

- o Fine-grained silica sand sizes may be slow to settle; may increase installation time or require installation by tremie pipe.

4.2-5 SEALS

An effective monitoring well seal prevents the vertical movement of ground water within the borehole and should not interfere with the water chemistry of the aquifer. The purpose of installing a monitoring well seal is to:

- Seal off and isolate a specific section of an aquifer to obtain information on the hydrogeologic and chemical characteristics at that location.

- Prevent migration of fluids from the ground surface into the borehole.

- Prevent contaminant movement from one section of an aquifer to another or between aquifers, especially to make sure that contaminated ground water does not enter contaminant-free geologic formations.

- Provide support for the well casing and prevent collapse of the borehole walls.

There are four types of seals used in monitoring well installations: surface seals, divider seals, bedrock seals, and annular seals.

4.2-5.1 Surface Seal (Apron)

A concrete seal around the top of the well is recommended even if the annular seal is carried to the surface. This concrete apron or seal should be shaped so that surface water flows away from the casing. Bentonite is not an acceptable material for surface seals because it will dehydrate and crack resulting in poor sealing properties. Based on the average depth of frost penetration in Massachusetts the surface seal should, if possible, extend a minimum of four feet below ground to prevent frost-heaving of the apron.

4.2-5.2 Divider Seal

A divider seal consists of a layer of bentonite slurry or pellets designed to prevent the liquid grout seal from plugging up the filter pack. This seal should be placed above the filter pack and below the annular seal. The minimum acceptable thickness is 6 inches; the recommended thickness is 2 feet.

4.2-5.3 Bedrock Seal

All open bedrock monitoring wells should be grouted, sealing the casing into the rock. A special exception to this rule is the case where the bedrock interface itself is being monitored.

4.2-5.4 Annular Seal

Annular seals are placed in the annular space above the divider seal to plug up the open space between the well casing and the borehole wall. It is extremely important that this seal consists of a low permeability material that will serve to inhibit the vertical movement of fluids within the borehole. If the well casing is in direct contact with the borehole wall it will not be possible to install an annular seal. A tight fit between the well casing and the borehole wall should serve to prevent the vertical movement of fluids along the outer wall of the casing. In certain specialized installations, such as Barcads, the annular seal consists of a 2-foot thick layer of bentonite pellets placed above and below the porous Barcad sampler. The importance of the annular seal becomes extremely significant when the well owner is ready to decommission the monitoring well. If the well owner can demonstrate that the monitoring well was properly sealed originally, decommissioning will be a much simpler and less costly procedure (see Section 4.6 Well Decommissioning). An annular seal is generally composed of one or a combination of the following sealants: neat cement, bentonite/cement slurries, or equivalent sealing agents.

4.2-6 SEALING MATERIALS

There are several types of sealants available for monitoring well installations. The selection of a well sealing material will depend on the depth of application, the chemistry of the water, the well casing material, and the purpose of the well program. Well sealants can be divided into two basic categories: solid sealants and grout sealants. These sealants are described below.

4.2-6.1 Solid Well Sealants

These materials are installed in a well bore in a solid form. Solid sealants are usually applied as divider seals between the filter pack and the annular seal or as the only seal in specialized installations.

4.2-6.1.1 Bentonite Pellets

Bentonite pellets consist of pre-formed pellets, usually ¼- to ½-inch in diameter; they are made from compressed sodium bentonite clay. When the pellets are hydrated with clean water, they swell to about 10 to 15 times their original volume. Because they hydrate rapidly, the pellets are prone to stick between the borehole wall and well casing (i.e. bridge) before reaching the bottom if they are manually dropped down the annular space.

Advantages

- Readily available.
- Provide a solid seal that can be immediately measured during installation.

Disadvantages

- Tendency to stick can make them difficult to install.

- o Installation can be slow in deep borings.

4.2-6.1.2 Coarse-grade Bentonite Chips

Coarse-grade bentonite consists of large chips of bentonite, usually 3/8- to 1-inch in size, resembling pea stone in appearance. Similar to bentonite pellets, bentonite chips will hydrate and expand when exposed to clean water. They are primarily intended for borehole decommissioning purposes but have been used as divider seals and shallow annular seals in monitoring wells. Due to their coarse grain-size, this material has limited use in monitoring well installations. Chips are not suitable for installation in small diameter holes because bridging may occur. Prior to installation, the chips should be sifted to remove the fines since, if the fines are not removed, they will clump as they hit the water and increase the chance of bridging (Gaber and Fisher, 1988).

Advantages

- o Provides a solid seal; its position can be verified by measurement immediately after installation.
- o Inexpensive.
- o Simple to install.

Disadvantages

- o Not suitable for small diameter boreholes.
- o Needs to be sorted.
- o Prone to bridging.
- o Relatively new product; further field testing needed.

4.2-6.2 Grout Seals

Grout is a mixture of powdered cement and/or bentonite and water to create a pumpable fluid. In some applications, aggregates and chemical additives are added to the mix to enhance the properties of the grout or to alter the setup rate. In monitoring well applications, grouts are typically installed as an annular seal between the monitoring well casing and the borehole wall. There are two basic types of grouts that are used as monitoring well seals: cement-based grouts and bentonite-based grouts. The applications, advantages, and disadvantages of these grouts are discussed below.

4.2-6.2.1 Cement-based Grouts

Cement-based grouts consist of a mixture of Portland cement and water. The sealant qualities of cement-based grouts are related to the type of cement that is used, the water-to-mix ratio, mixing methods, and installation methods. The rate at which a cement-based grout will set is principally related to the chemical composition of the cement. Generally, Portland Type I or II cement is used for monitoring well seals. Table 4.2-4 summarizes the characteristics of the different ASTM cement types.

A by-product of the chemical reactions that result in hardening of the cement is heat. The amount of heat that is produced during hydration is related to the chemical composition of the cement, the thickness and total volume of grout emplaced, and the ambient formation temperatures (Gaber and Fisher, 1988). The heat of hydration should be considered when grouting boreholes with plastic casing, especially in deep applications. There are three types of cement-based grouts used in monitoring well applications: neat cement, neat cement with bentonite, and concrete.

(a) Neat Cement:

Neat cement is a mixture of powdered cement and water; no sand or aggregate is added to the mix. The sealing qualities of neat cement depend on the water-to-cement mix ratio. Table 4.2-5 presents the properties of neat cement based on the gallons of water per bag of cement. All neat cement shrinks as it sets, and shrinkage increases with the water content of the cement mix. Consequently, the addition of too much water will adversely affect the sealant properties. Even properly mixed, a pure neat cement will shrink approximately 18 to 20 percent as it sets (Williams and Evans, 1987). Due to this excessive shrinkage, pure neat cement has limited application as a monitoring well sealant.

(b) Neat Cement with Bentonite:

The addition of a small amount of bentonite to a neat cement slurry will improve the sealing properties of the grout by reducing the shrinkage and separation of the concrete materials in the borehole. The addition of bentonite also decreases the density of the mix and increases the viscosity and fluidity. Although the addition of bentonite reduces the shrinkage and increases the pumpability of the grout, it also results in a decrease in the final strength of the grout and may increase its vulnerability to chemical attack (Williams and Evans, 1987). Generally, a mix consisting of between 5 and 15 percent bentonite is desirable.

While it is recommended that the proportion of bentonite be limited to approximately 5 percent or less, some very porous materials (e.g., coarse gravel) may require more bentonite to reduce the loss of grout into the formation.

(c) Concrete:

Concrete is a mixture of Portland cement, sand, and water. The addition of the aggregate to the neat cement grout increases the strength of the material, reduces the shrinkage, and typically results in tighter bonding compared to neat cement grouts. Concrete is typically used for the surface seal in a monitoring well installation. Concrete is generally used to cap grout or bentonite seals because it is less prone to cracking and is easy to mix. Concrete is not suitable as a sealant for annular spaces because it has a tendency to separate in water, may bridge during installation, and is difficult to pump.

(d) Cement Additives:

In some instances, chemical additives can be mixed with the grout to accelerate the rate of setup. Calcium chloride is the most common cement accelerator, and is usually added in quantities of two to four percent by weight (Gaber and Fisher, 1988). Although accelerators have application in emergency grouting operations, they are not recommended for use in monitoring well installations due to their impact on water chemistry.

4.2-6.2.2 Bentonite-based Grouts

Bentonite is a montmorillonite clay that will expand 10 to 12 times in size upon hydration (Gaber and Fisher, 1988). There are both sodium- and calcium-rich varieties of bentonite. Sodium-rich bentonite is preferred for monitoring well applications because of its superior expansive qualities. Bentonite-based drilling muds have been used for many years in the water well industry, but only in the past decade has there been research into the use of bentonite grouts as permanent seals in monitoring wells.
There are basically three types of bentonite-based grouts: heavy bentonite grout, high-solids bentonite grout, and granular bentonite grout.

(a) Heavy Bentonite Grout:

Heavy bentonite grout consists of a mix of bentonite and water, consisting of 10 percent bentonite by weight. The grout must have a high density and high gel strength in order to be effective. The proper bentonite-to-water mix will result in a high viscosity fluid that can be difficult to pump. Improper mixing or installation can result in the bentonite settling out of settling of the water. Due to their difficult mixing and pumping requirements, heavy-bentonite grouts have limited application for monitoring well installations.

(b) High-solids Bentonite Grout:

High-solids bentonite grout consists of a mix of bentonite, water, and an initiator to produce a grout that is 15- to 20-percent solids. The addition of the initiator, usually magnesium oxide, is required to obtain the high percent of solids. Mixing is more complex than with other grouts. High-solids bentonite slurries require a Venturi-jet mixer, mud-rotary pump, or a paddle mixer to produce a suitable mix (Gaber and Fisher, 1988). Properly mixed high-solids bentonite grouts are easy to pump and provide a flexible, low-permeability seal. This material sets up into a plastic clay putty in approximately 8 to 24 hours. Generally, a solid seal of cement or solid bentonite is required at the base and the top of this grout.

(c) Granular Bentonite Slurries:

Instead of powdered bentonite, granular bentonite slurries utilize bentonite particles ranging from 8- to 20-mesh in size (Gaber and Fisher, 1988). The comparatively smaller surface area of the granular bentonite results in a slower rate of adsorption. A proper granular bentonite slurry mix should contain 15- to 20-percent bentonite by weight. In order to obtain a pumpable mix of 15- to 20-percent bentonite, a synthetic organic polyacrymide polymer is sometimes added to suppress hydration and delay swelling. The addition of synthetic polymers is NOT recommended for the installation of monitoring wells unless prior approval is obtained from DEP. Similar to high-solids grouts, granular bentonite grouts require a blade or paddle mixer; a centrifugal pump is not capable of mixing this grout. An advantage of the granular grout mix is that, unlike other bentonite grouts, it provides mechanical stability to the casing and borehole walls (Gaber and Fisher, 1988). Granular slurries can be difficult to install, due to problems resulting from premature expansion of the bentonite.

Table 4.2-6 provides a comparison of the advantages and disadvantages of cement-based and bentonite-based grouts.

4.2-7 PROTECTIVE CASINGS

A protective well casing is required for all monitoring wells to protect the well from damage, leakage, tampering, and vandalism. Protective well casings are generally constructed of steel and have a locking cap. Two basic types of protective casings are used in monitoring well installation: an above-ground casing and a flush-mount casing, or road box (see Figures 4.2-4 through 4.2-6).

4.2-7.1 Above-ground Protective Casing

Above-ground protective well casings are typically constructed from steel or cast iron pipe sections, generally 5 to 7 feet in length and 4 inches or greater in diameter. Iron or steel protective casings are much preferred over plastic because they are less susceptible to damage and vandalism. If the protective casing has a screw-on cap, making it air-tight, the protective casing as well as the riser pipe should be vented with a small hole. The protective casing should have a hasp on the top so it can be locked with a padlock. The padlock should be corrosion-resistant; it is advisable that all the padlocks at a site be keyed alike for simplicity.

In some heavily trafficked areas, the protective casing may be subject to damage by vehicles or snowplows. Additional posts or casings should be installed to provide a buffer zone around the well (Figure 4.2-7). Three posts placed in a triangle, each about two feet from the well, should be sufficient. Fewer posts may be necessary if the traffic pattern is well defined.

4.2-7.2 Flush-mount or Road-box Casing

A flush-mount protective casing is used where the well installation must be installed flush with the ground surface, such as in roadways, parking lots, and sidewalks. Flush-mount well installations also help to disguise the well location and reduce the potential for vandalism. As shown on Figure 4.2-5, the flush-mount installation can be installed with single riser and a valve-box or road-box. Alternatively, a standard type manhole can be installed directly over the well riser pipe with locking protective casing. This type of flush-mount installation is shown in Figure 4.2-6. Generally, manhole covers cannot be locked, so a padlock is placed directly on the protective casing. Some road boxes have a five-sided bolt on the top that holds the cover on. A special wrench is required to open these boxes. A rubber gasket should be placed between the manhole cover and the lip to prevent leakage of surface water into the manhole. When potential high water table conditions exist at flush-mount installations, water tight caps should be placed on top of the riser. If well drained soil conditions exist, granular material should be placed inside the manhole around the well riser to drain surface water that may seep in around the cover.

The protective casing must be properly sized for the borehole diameter. Generally, it is best if the protective casing is close to the size of the borehole so that it fits snugly.

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SECTION 4.2
SELECTION OF WELL CONSTRUCTION MATERIALS

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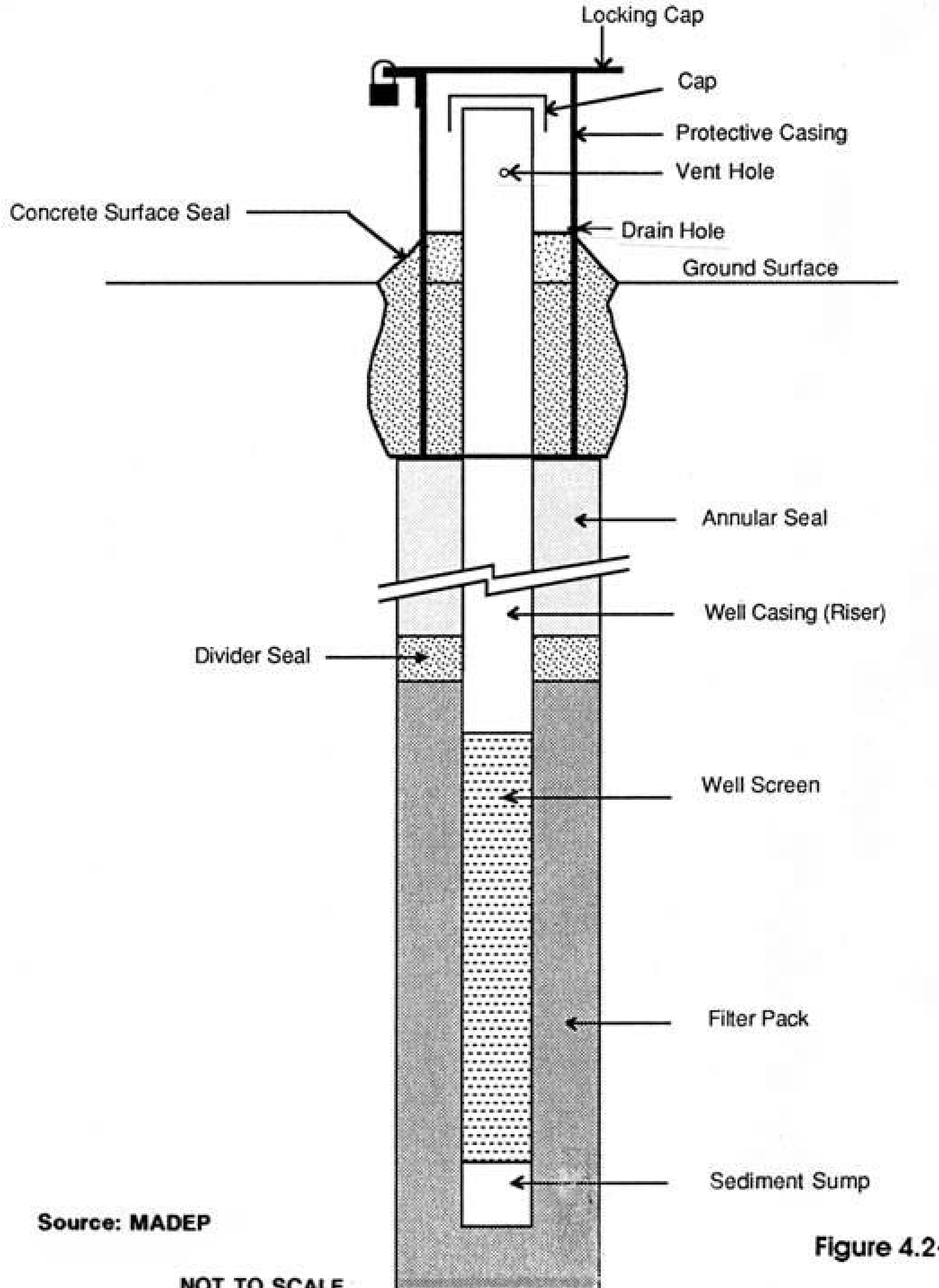

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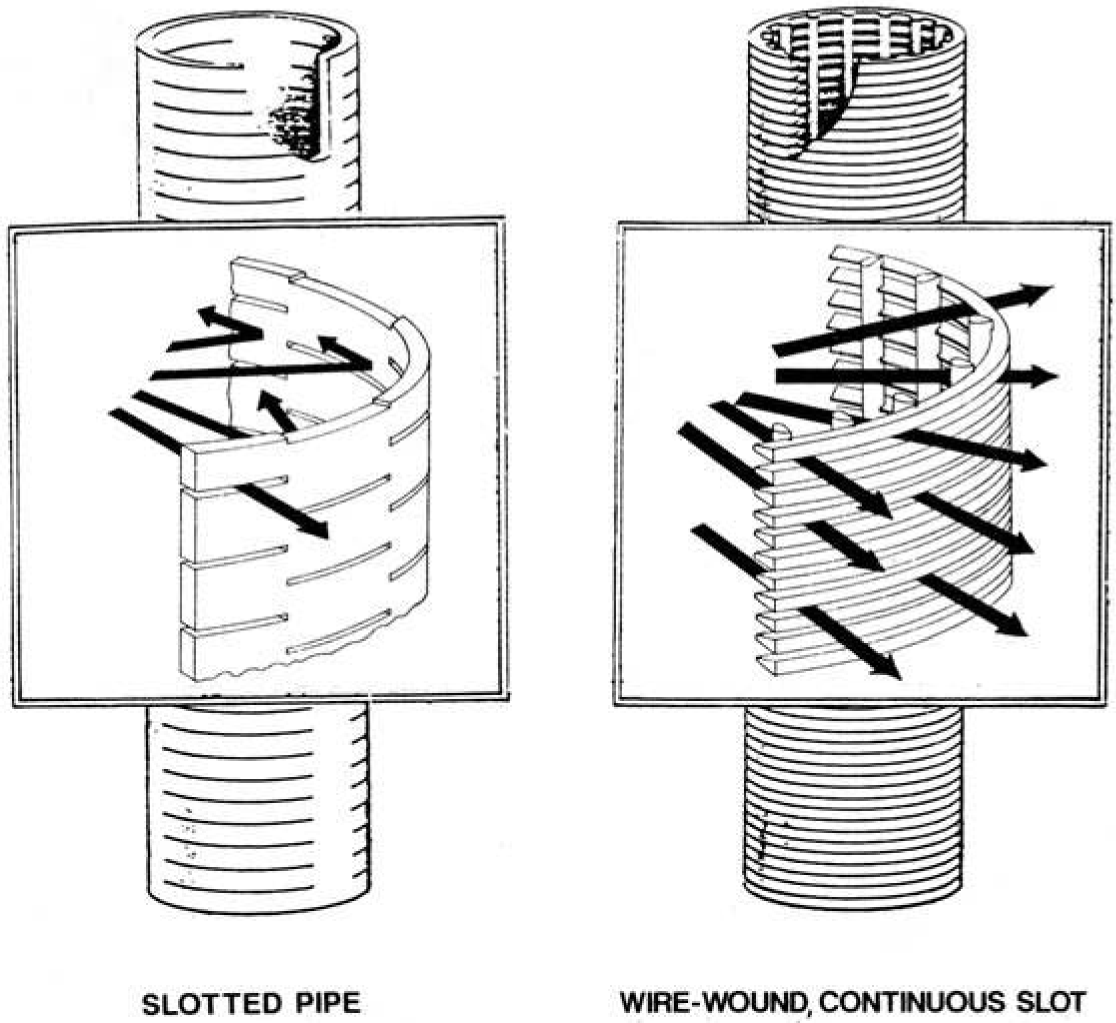
Figure 4.2-1

Well Component Diagram.



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Source: Johnson Division (1987 Catalogue)

Figure 4.2-2

Types of Well Screen Slot.

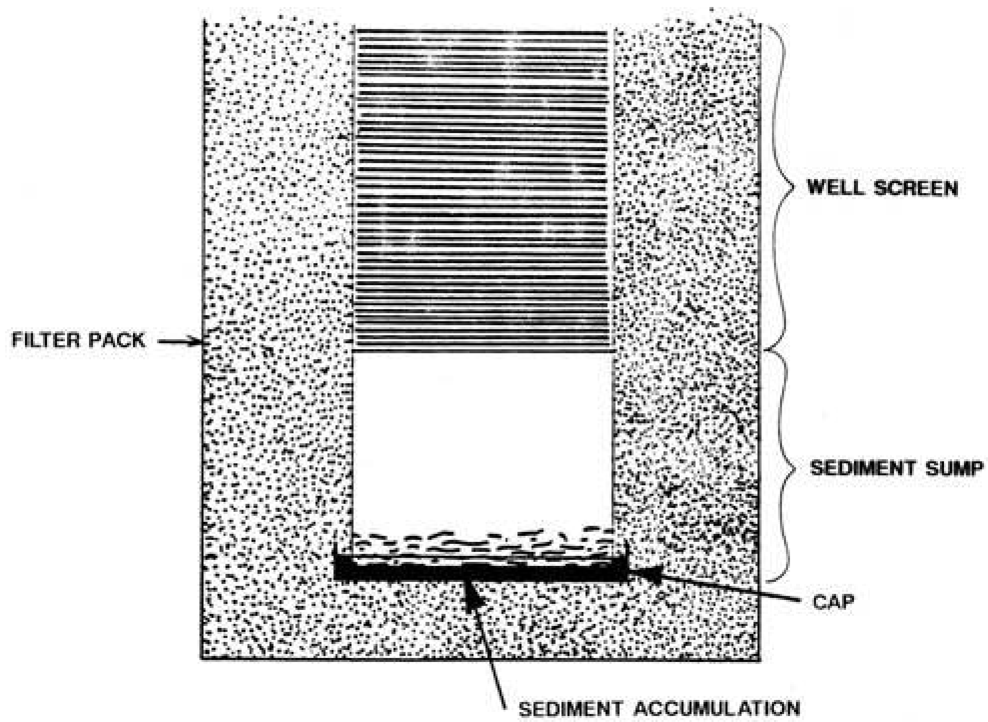

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Figure 4.2-3

Diagram of a Sediment Sump.

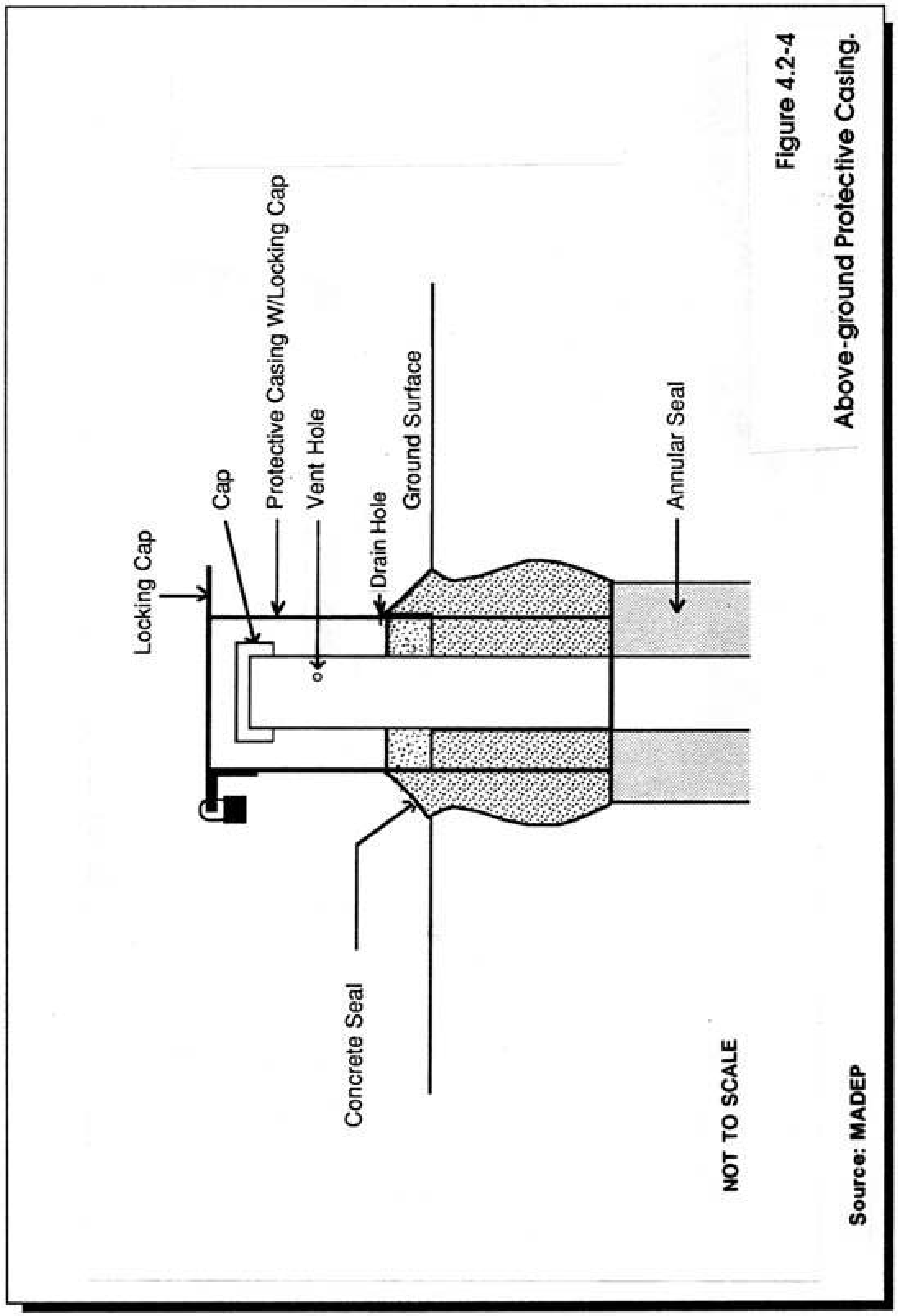

Figure 4.2-4
Above-ground Protective Casing.

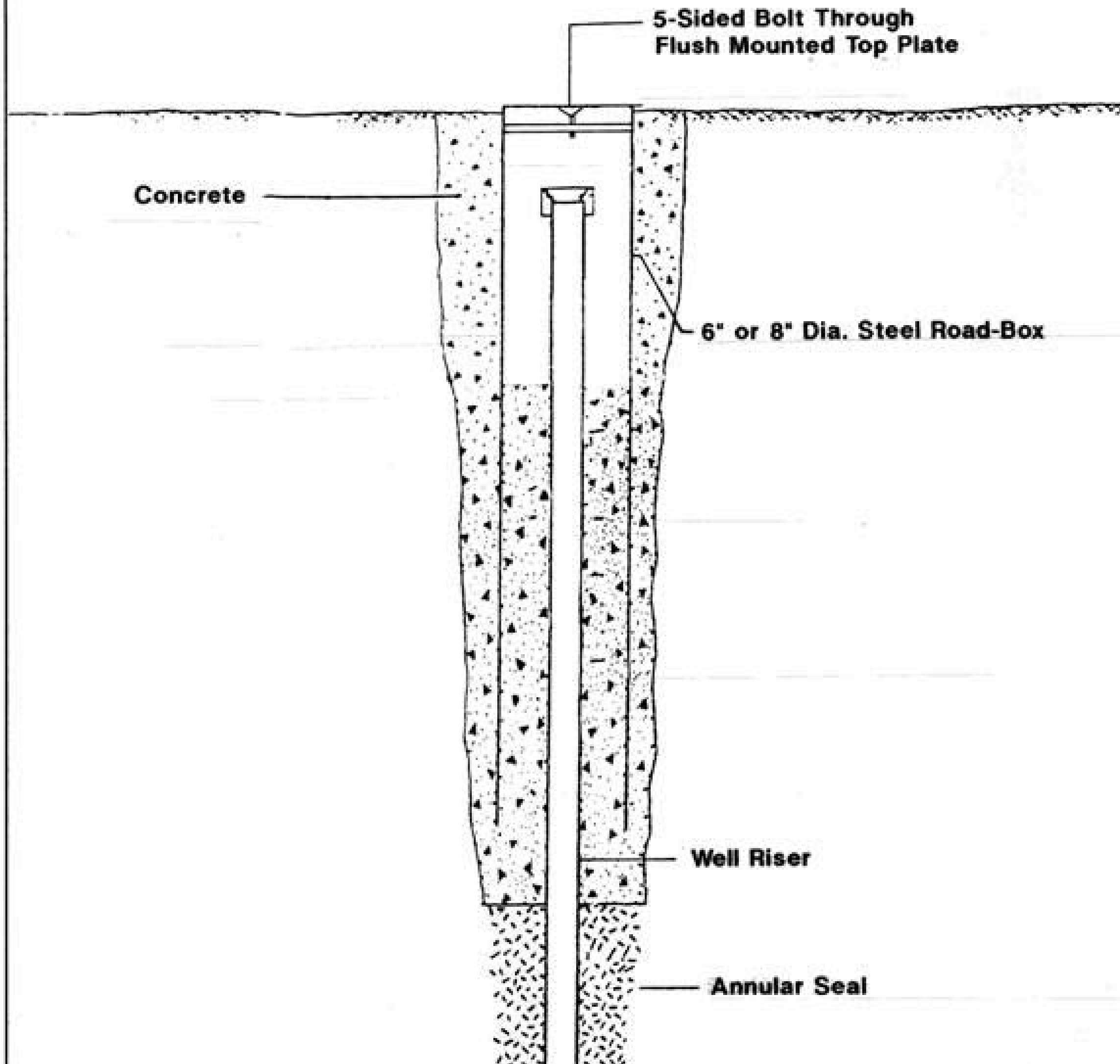

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Figure 4.2-5

Source: MADEP

Flush-mount Road-box.

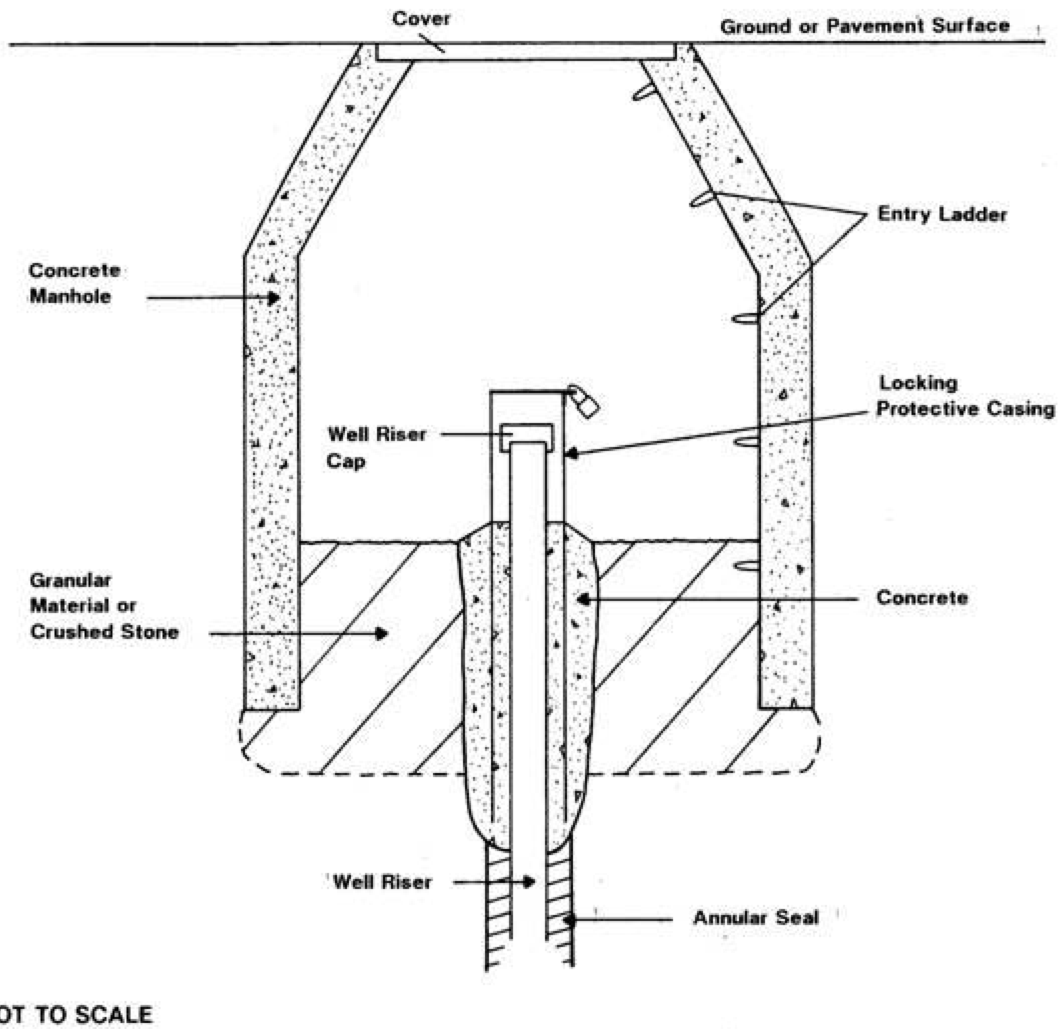

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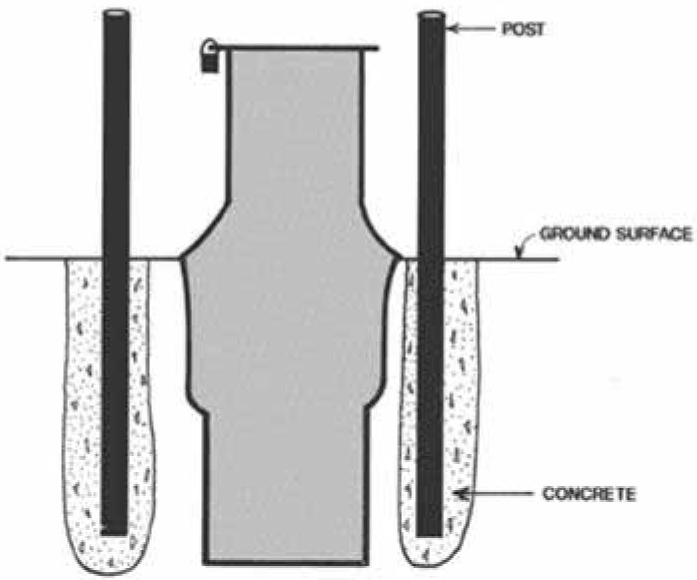
Figure 4.2-6

Manhole -type Road-box.



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Source: MADEP

Figure 4.2-7

Protective Posts Around a Monitoring Well.

Type	Advantages	Disadvantages
PVC (Polyvinyl-chloride)	• Lightweight • Excellent chemical resistance to weak alkalies, alcohols, aliphatic hydrocarbons, and oils • Good chemical resistance to strong mineral acids, concentrated oxidizing acids, and strong alkalies • Readily available • Low priced compared to stainless steel and Teflon	• Weaker, less rigid, and more temperature sensitive than metallic materials • May adsorb some constituents from groundwater • May react with and leach some constituents from groundwater • Poor chemical resistance to ketones, esters, and aromatic hydrocarbons
Polypropylene	• Lightweight • Excellent chemical resistance to mineral acids • Good to excellent chemical resistance to alkalies, alcohols, ketones, and esters • Good chemical resistance to oils • Fair chemical resistance to concentrated oxidizing acids, aliphatic hydrocarbons, and aromatic hydrocarbons • Low priced compared to stainless steel and Teflon	• Weaker, less rigid, and more temperature sensitive than metallic materials • May react with and leach some constituents into groundwater • Poor machinability — it cannot be slotted because it melts rather than cuts
Teflon	• Lightweight • High impact strength • Outstanding resistance to chemical attack; insoluble in all organics except a few exotic fluorinated solvents	• Tensile strength and wear resistance low compared to other engineering plastics • Expensive relative to other plastics and stainless steel
Kynar	• Greater strength and water resistance than Teflon • Resistant to most chemicals and solvents • Lower priced than Teflon	• Not readily available • Poor chemical resistance to ketones, acetone
Mild steel	• Strong, rigid; temperature sensitivity not a problem • Readily available • Low priced relative to stainless steel and Teflon	• Heavier than plastics • May react with and leach some constituents into groundwater • Not as chemically resistant as stainless steel
Stainless steel	• High strength at a great range of temperatures • Excellent resistance to corrosion and oxidation • Readily available • Moderate price for casing	• Heavier than plastics • May corrode and leach some chromium in highly acidic waters • May act as a catalyst in some organic reactions • Screens are higher priced than plastic screens

Source: Driscoll (1986)

Table 4.2-1

Basic Well Casing and Screen Material Composition

Diameter of Casing or Hole (In)	Gallons per foot of Depth	Cubic Feet per Foot of Depth	Liters per Meter of Depth	Cubic Meters per Meter of Depth
1	0.041	0.0055	0.509	0.509×10^{-3}
1½	0.092	0.0123	1.142	1.142×10^{-3}
2	0.163	0.0218	2.024	2.024×10^{-3}
2½	0.255	0.0341	3.167	3.167×10^{-3}
3	0.367	0.0491	4.558	4.558×10^{-3}
3½	0.500	0.0668	6.209	6.209×10^{-3}
4	0.653	0.0873	8.110	8.110×10^{-3}
4½	0.826	0.1104	10.26	10.26×10^{-3}
5	1.020	0.1364	12.67	12.67×10^{-3}
5½	1.234	0.1650	15.33	15.33×10^{-3}
6	1.469	0.1963	18.24	18.24×10^{-3}
7	2.000	0.2673	24.84	24.84×10^{-3}
8	2.611	0.3491	32.43	32.43×10^{-3}
9	3.305	0.4418	41.04	41.04×10^{-3}
10	4.080	0.5454	50.67	50.67×10^{-3}
11	4.937	0.6600	61.31	61.31×10^{-3}
12	5.875	0.7854	72.96	72.96×10^{-3}
14	8.000	1.069	99.35	99.35×10^{-3}
16	10.44	1.396	129.65	129.65×10^{-3}
18	13.22	1.767	164.18	164.18×10^{-3}
20	16.32	2.182	202.68	202.68×10^{-3}
22	19.75	2.640	245.28	245.28×10^{-3}
24	23.50	3.142	291.85	291.85×10^{-3}
26	27.58	3.687	342.52	342.52×10^{-3}
28	32.00	4.276	397.41	397.41×10^{-3}
30	36.72	4.909	456.02	456.02×10^{-3}
32	41.78	5.585	518.87	518.87×10^{-3}
34	47.16	6.305	585.68	585.68×10^{-3}
36	52.88	7.069	656.72	656.72×10^{-3}

1 Gallon = 3.785 Liters
1 Meter = 3.281 Feet
1 Gallon Water Weighs 8.33 lbs. = 3.785 Kilograms
1 Liter Water Weighs 1 Kilogram = 2.205 lbs.
1 Gallon per foot of depth = 12.419 liters per foot of depth
1 Gallon per meter of depth = 12.419×10^{-3} cubic meters per meter of depth

Table 4.2-2

Source: Driscoll (1986)

Volume of Water in Casing or Hole

NOMINAL PIPE SIZE [inches]	GAUGE NUMBER OR SLOT NUMBER										
	10	12	14	18	20	25	30	40	50	80	100
3/4	.79	.88	1.09	1.39	1.46	1.88	2.18	2.89	3.64	5.77	7.30
1	1.09	1.37	1.57	1.96	2.18	2.76	3.26	4.34	5.43	6.86	10.84
1 1/4	1.83	2.19	2.56	3.27	3.63	4.54	5.45	7.25	9.05	14.47	18.07
1 1/2	2.19	2.60	3.05	3.91	4.34	5.44	6.49	8.67	10.86	17.29	21.69
2	2.89	3.49	4.06	5.22	5.78	7.25	8.65	11.56	14.47	23.05	28.88
2 1/2	3.86	4.68	5.39	6.99	7.69	9.66	11.53	15.39	19.25	30.77	38.47
3	3.87	4.67	5.39	6.97	7.69	9.67	11.54	15.37	19.23	30.76	38.43
4	4.86	5.79	6.74	8.68	9.64	12.09	14.44	19.23	24.02	38.43	48.04
6	6.76	8.08	9.43	12.16	13.47	16.86	20.18	26.89	33.63	53.78	67.23
8	8.67	10.39	12.13	15.57	17.29	21.63	25.96	34.57	43.26	69.14	86.46
10	11.58	13.87	16.14	20.75	23.09	28.84	34.57	46.09	57.67	92.17	115.29
12	13.46	16.16	18.84	24.22	26.89	33.63	40.35	53.77	67.28	107.53	134.45
14	15.39	18.47	21.57	27.67	30.73	38.43	46.09	61.45	76.82	122.89	153.67
16	17.29	20.79	24.21	31.16	34.57	43.23	51.86	69.13	86.44	138.27	172.80

Table 4.2-3

Total Slot Area of Screen of Various Gauges in Square Inches Per Foot

Source: Johnson Cat.

Type I	- General purpose cement suitable where special properties are not required.
Type II	- Moderate sulfate resistance. Lower heat of hydration than Type I. Recommended for use where sulfate levels in groundwater are between 150 and 1500 ppm.
Type III	- High-early-strength. Ground to finer particle size which increases surface area and provides faster curing rate. High early strength results in reduction of time period before drilling may resume from 48 hours to 12 hours. When Type III cement is used, the water to cement ratio must be increased to 6.3 to 7 gallons of water per sack.
Type IV	- Low heat of hydration cement designed for applications where the rate and amount of heat generated by the cement must be kept to a minimum. Develops strength at a slower rate than Type I.
Type V	- Sulfate-resistant cement for use where ground water has a high sulfate content. Recommended for use where sulfate levels in groundwater exceed 1500 ppm.

Table 4.2-4

ASTM Cement Designations

Source: Gaber and Fisher (1988)

ASTM CEMENT CLASS	SLURRY WEIGHT (lbs/gal)	MIX WATER REQUIRED (gals/sack)	SLURRY YIELD (Ft^3/sack)	PERCENTAGE OF MIX WATER BY WEIGHT OF CEMENT
A	15.6	5.20	1.18	46
B	15.6	5.20	1.18	46
C	14.8	6.32	1.32	56
G	15.8	4.97	1.15	44
H	16.5	4.29	1.05	38

Source: Schlumberger (1984)

Table 4.2-5

Properties of Neat Cement Slurries

GROUT PROPERTIES

	ADVANTAGES	DISADVANTAGES
CEMENT-BASED GROUTS	Suitable Permeability Easily Mixed & Pumped Hard-Positive Seal Supports Casing Suitable for Most Formations Proven Effective Over Decades of Field Use Poperties Can Be Altered With Additives Readily Available	Shrinkage & Settling Long Curing Time High Density Results in Loss To Formations Heat of Hydration Affects Water Quality Equipment Clean-Up Essential Casing Cannont Be Moved After Grouting
BENTONITE-BASED GROUTS	Suitable Permeability With High Solids Grouts Non-Shrinking & Self-Healing No Heat of Hydration Low Density No Curing Time Required Casing Moveable After Grouting	Premature Swelling and High Viscosity Result In Difficult Pumping Difficult Mixing Subject To Wash Out In Fractured Bedrock Subject To Failure From Contaminated Water Equipment Clean-Up Difficult Limited Field Experience Usage Instructions Vary For Each Product Limited Availability

Table 4.2-6

Source: Gaber and Fisher (1988)

Grout Properties - Advantages and Disadvantages

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 4.3 WELL INSTALLATION PROCEDURES

SECTION 4.3
WELL INSTALLATION PROCEDURES

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SECTION 4.3
WELL INSTALLATION PROCEDURES

4.3-1 PURPOSE

The proper installation of monitoring wells is an essential part of all hydrogeologic investigations. The proper installation depends on good communication and cooperation between the drilling contractor and field personnel. Quality well installations require thoughtful consideration of several interrelated topics including the objective(s) of the well installation program, selection of the appropriate drilling method, network design, and well construction materials. Information and technical guidance on these aspects of monitoring well construction are contained in other sections of these Standard References: Section 3.2 Drilling Methods, Section 4.1 Network Design, and Section 4.2 Selection of Well Construction Materials. The reader should refer to these sections prior to specifying well materials and installation procedures.

The techniques described in the following subsections are some of the common and effective methods that can be used to install monitoring wells. Other methods may be utilized provided that the performance and integrity of the well components are maintained. A drilling contractor experienced in monitoring well installation can offer many helpful suggestions on both standard and innovative well installation methods. Discussion of a proposed well installation program with a drilling contractor prior to undertaking the field program is strongly recommended.

Improperly installed monitoring wells can have serious consequences. Data obtained from such wells can be incorrect and/or misleading, resulting in erroneous interpretations and conclusions concerning potentiometric head conditions, the extent of contamination, contaminant concentrations, and the source or receptor of contamination. Frequently, inadequate attention is given to the proper preparation and installation of monitoring well seals. Inadequately sealed wells can serve as conduits for the vertical movement of contaminants. This is of particular concern when installing wells into the lower portion of an unconsolidated aquifer and into bedrock. A detailed discussion of the preparation and installation of monitoring well seals is contained in this Standard Reference (SR).

This SR focuses primarily on the installation of single standpipe wells, as this is the type of well most commonly installed. Multi-level well nests and specialized wells in a single borehole require specialized installation techniques not covered in this section. Individuals involved in the installation of these types of wells should discuss the recommended methods with the manufacturer or his representative.

4.3-2 COMPONENTS OF THE INSTALLATION

In an unconsolidated formation the basic components of a monitoring well installation are:

- o placement of the well screen and riser pipe
- o placement of the filter pack
- o placement of the divider seal
- o placement of the annular seal
- o placement of the protective casing and surface seal

An open bedrock well will always require the installation of a grout seal that ensures that the well casing is firmly embedded in the rock. A typical open rock well installation is shown on Figure 4.3-3.

Simply stated, installation involves positioning the well screen in the geologic unit of interest and attaching a string of riser pipe to the screen. The riser pipe or well casing extends to or slightly above the ground surface. The screened section is then backfilled with a granular filter pack material such as silica sand or, in some special cases, with formation materials. A divider seal typically consisting of bentonite pellets is placed above the filter pack to seal off the monitoring zone. The annular space above the divider seal is then filled with more impervious material. Grout slurries consisting of bentonite, cement or a mixture of the two materials are generally recommended for annular seals. A protective casing or road box is installed in a concrete seal at the ground surface.

The general requirements and recommended installation methods for each of these monitoring well components are described in the following sections and are shown on Figure 4.3-1. In general these techniques are similar for both unconsolidated deposits and bedrock. A typical bedrock well installation with screen and riser is shown on Figure 4.3-2. It is important to note that it is recommended to enlarge the hole into the upper bedrock surface to allow for a more reliable installation and measurement of the filter pack and divider seal materials.

The most common variation to this installation sequence is with the open bedrock well technique commonly used for water supply wells. The open rock well technique generally consists of: advancing a steel casing into bedrock, grouting the casing permanently into the upper rock material, and then advancing the hole through the grout and rock to the desired depth. A well screen is generally not used with this technique and the drill casing becomes the permanent well casing.

4.3-3 INSTALLATION OF SCREEN AND WELL CASING

4.3-3.1 Borehole Preparation

In preparation for the installation of a monitoring well, the borehole should be checked for depth using some type of weighted measuring tape. In most instances, drilling waters should be flushed with clean potable water until the return is clear and free of sediment, if possible. To check for unstable rock or soil conditions, a second measurement is advisable. When hollow-stem auger equipment is used for the installation of monitoring wells, it is often recommended that the auger be flushed (i.e., washed) to the bottom to remove any loose material. In contrast, the drive-and-wash technique generally maintains a cleaner casing throughout the drilling phase.
If the borehole has been advanced beyond the desired well depth, it will be necessary to backfill the lower part of the hole up to the required depth of the well. It is important to backfill and seal the deeper hole so that, if required by the sampling design plan, the well will produce water samples from a discrete zone.

4.3-3.2 General Requirements

For monitoring wells installed in either the bedrock or the overburden, important considerations in the placement of the screen and well casing include the following:

- The borehole should be of a diameter adequate to allow for proper placement of the filter pack and seals.

- If necessary, decontamination of the well riser and screen should be carried out in accordance with a procedure that is similar to that presented in Sections 3.3 and 6.5 of these Standard References.

- The casing and screen should be centrally positioned in the borehole. This will assure even placement of the filter pack and seals and will reduce the possibility and chance for the occurrence of dead spaces or voids.

- The screen and riser pipe should be vertically plumb. A vertical well screen and casing will assure that accurate water-level measurements are obtained. Also, straight, vertical installations will provide for easier installation of the filter pack and seal materials, and facilitate sampling in the future.

- The casing sections should be firmly joined with leak-tight joints. Most well casing consists of threaded, flush-joint pipe. Studies have shown that in some cases threaded joints leak, allowing water or undesirable fluids to seep into the well. Teflon tape or O-rings can be used on the joints to help prevent leakage. Joints should not be sealed or glued with any substance that could potentially contaminate the well.

- The source and purity of filter sand and bentonite should be checked prior to their use in the borehole. Drilling contractors and suppliers usually furnish, on request, quality assurance documentation for these materials.

- The well should be vented. A small vent or hole should be drilled below the depth of the cap into the final section of riser pipe. This will allow gas and air to escape and facilitate accurate measurements of potentiometric head. Vent holes should not be used on flush-mount road box installations when there is the potential for infiltration from ground or surface water.

- The length of the casing above the ground surface (i.e., stick-up) should be measured and recorded.

4.3-3.3 Centralizers

The use of centralizing techniques is both advantageous and complex. The complexity is attributable to the installation of the filter pack and seals within a more restricted annulus.

Centralizing devices are recommended to properly position the well casing in the center of certain borehole (i.e., deep holes or fine-grained formations). Centralizers consist of collars that are attached to the well screen and riser, keeping it positioned in the center of the borehole. This type of device restricts the annular space and may create problems when placing filter sand, bentonite pellets, or grout through a tremie tube. If centralizers are used, it may be advantageous to modify them in order to facilitate the installation of filter sand and seals. Modification is often made by removing a portion of the centralizing device. If this cannot be done easily, it is sometimes advisable to place a centralizer only at the bottom of the installation.

4.3-4 FILTER PACK

4.3-4.1 General Requirements

The filter pack surrounds the screened section and restricts fine-grained particles from entering the well screen. The filter pack supports the borehole walls and prevents the wall from collapsing in or around the well screen. The important aspects of filter pack installation are as follows:

- The filter pack should provide complete and even coverage around the well screen. A properly installed filter pack does not contain any voids. Sidewalls or cuttings from the borehole should not be allowed to collapse or collect around the screen when formation materials are unsuitable.

- A minimum of two feet of filter pack above the well screen is recommended. This extra thickness will prevent seal material, particularly grout, from settling in and around the well screen. When coarse filter sand is used around the well screen, a finer sand filter pack should be placed along the riser between the screen and the divider seal. In all cases, the depth to the top of the filter pack should be verified by measurement. Extension of the filter pack above the screen effectively lengthens the monitoring zone. Adequate time must be allowed for the filter pack to settle in the borehole prior to measurement, particularly in deep boreholes.

4.3-4.2 Installation

Prior to installation, the volume of filter material necessary to fill the annular space between the well screen and the borehole wall should be calculated. A simple way to do this is to place a section of well screen in a piece of casing or pipe that is equivalent to the borehole diameter, and determine the number of pails, jars or cans necessary to fill a 1- or 2-foot length of the annular space. The total length of the filter pack can be multiplied by this number to determine the estimated quantity of filter pack necessary. During the installation the total amount of filter pack installed should be recorded. Variations in the calculated volume and the actual amount installed should be noted. When installing wells in hollow-stem auger holes, it is important to remember that the inside diameter of the augers is much smaller than the borehole diameter. The amount of sand necessary to fill the outside diameter should be determined prior to installation. There are two basic methods by which filter packs can be installed: the tremie method and the free-fall method. The selection of the method of filter pack installation is dependent on the particle size of the filter pack material, the annular space between the borehole wall and the well screen, and the depth to the water table.

4.3-4.2.1 Tremie Method

The tremie method involves placing a small diameter pipe down the annular space between the well screen and the casing or augers. The filter material is then poured or pumped (as a slurry) into the pipe and allowed to settle in and around the well screen. The top of the sand pack should be verified by measurement. As the sand pack is installed, the tremie pipe must be continually retracted in 1- to 2-foot increments to prevent the pipe from becoming buried in the filter pack. The tremie method is particularly suitable for deep well installations or instances where the water table is deep, because it eliminates the hazard of the filter pack becoming caught (i.e. bridging) in the annulus between the well pipe and the drill casing and plugging the borehole. When graded filter packs are used the tremie method prevents segregation of the fine and coarse particles that might occur with the free fall method of emplacement. Bridging may also occur in the tremie pipe.

4.3-4.2.2 Free-Fall and Tamp Method

The free-fall method consists of pouring a pre-measured quantity of sand down the hole from the ground surface. The free-fall method is best suited for shallow well installations where the water table is relatively close to the ground surface. Sand is poured down the annular space between the outside of the screen and well riser and the inside of the casing or augers. The sand should be added slowly to avoid bridging. If bridging does occur, the addition of water or a short quick movement the drill casing will usually free the sand pack. Care should be exercised when using a mechanical method to free bridged sand as it may damage the well pipe by unscrewing or pulling apart the well pipe at a coupling. The addition of water, if possible, is the preferred method as it places less stress on the well pipe.

A small amount (i.e., approximately 1 to 2 linear feet) of sand can be allowed to fill the bottom of the casing. The casing or augers should then be slowly retracted approximately 0.5 to 1 foot so that the filter pack can fill the space between the well screen and the borehole wall. Sand should remain in the bottom of the casing or augers at all times so that the natural soil does not cave around the screen. When augers are used, the rate at which the sand drops out of the auger as they are pulled is very rapid, because the borehole diameter is so much larger than the annular space between the inside of the auger and the well screen. Special care should be taken to maintain a continuous sand filter around the screen interval. The top of the sand pack should be tamped and measured with weighted tape or rod to verify its location each time the casing is retracted. This process should be repeated until the desired length of filter pack has been installed.

4.3-4.2.3 In-place Filter Pack

In coarse-grained soils the in-place formation materials may provide a suitable filter pack for the well screen. In this case the borehole casing or augers are retracted to the depth of the top of the filter pack and the borehole walls are allowed to collapse around the screen. The casing or augers should be retracted slowly and steadily to prevent voids from occurring. As with the other placement methods, the top of the filter pack should be verified by measurement. If additional length of filter pack is needed, the casing can be retracted further to allow more natural cave-in, or artificial pack material can be added.

4.3-5 SEALS

4.3-5.1 General Requirements

Well seals are a very important part of any monitoring well installation. Well seals isolate the well screen at the desired depth within the formation. Additionally, properly installed well seals prevent the vertical migration of fluids and contaminants along the annular space of the borehole. Important considerations in the installation of well seals are:

- The well seal should form a continuous, impervious column in the borehole to prevent the migration of fluids or contaminants either up or down the annular space. It should be noted if the surrounding soil or fill material is very coarse, the material used to seal the well may migrate into the surrounding material sufficiently to threaten the integrity of the well itself. When the volume of seal material used exceeds the volume of the borehole, other techniques such as the addition of more bentonite to slurries and grouts or the use of solid bentonite pellets should be considered to fill the annular space.

- The seal material should be of a durable, non-shrinking material. This requires the selection of the appropriate seal material, as well as the proper mix and installation.

- The location of the seal in the borehole should be verified by direct measurement.

4.3-5.2 Types of Well Seals

Well seals can be divided into three categories: divider seals, annular seals, and surface seals. The divider seal is one placed directly on top of the filter pack and below the annular seal, isolating the screened zone vertically from the remainder of the borehole. The annular seal is placed above this divider seal and fills much of the remaining borehole length. Bentonite, cement, and cement/bentonite grout and slurry mixtures are most often used as annular seal materials. Concrete is the most common surface seal material.

4.3-5.2.1 Divider Seals

Generally, divider seals consisting of either bentonite pellets or bentonite slurry are placed on top of the filter pack to isolate the screen zone in the desired strata. It is recommended that dry bentonite, consisting of 1/4- or 1/2-inch pellets, be used if the seal is above the water table and that a bentonite slurry be used below the water table. Bentonite pellets can be used below the water table if the water depth is moderately shallow (see Section 4.2). The thickness of this layer ranges generally from 2 to 5 feet. The minimum thickness of this layer is 6 inches. Extra caution should be taken when pellets are placed below the water table. Slurried bentonite seals should always be placed through a tremie pipe. In addition to forming a seal to prevent the migration of groundwater from higher strata, the divider seal is used to prevent the migration of annular sealant into the filter pack.

4.3-5.2.2 Annular Seals

Annular seals are placed above the divider seal, between the well casing and the borehole walls. The annular seal should be a low permeability material designed to prevent vertical migration of fluids and provide structural support for the casing. Grout mixtures are generally used for annular seals. If they are properly mixed and correctly installed, grout can be an effective well seal. The use of the correct bentonite/cement/water mix ratios, as well as proper mixing and placement are essential elements in obtaining an effective grout seal. Section 4.2 of these Standard References describes more fully the grout mixtures. Grout for the annular seal below the water table should always be placed through a tremie pipe.

4.3-5.2.3 Surface Seals

The surface seal is installed to secure the protective casing around the wellhead and to prevent infiltration of surface water around the well riser. The top 3 to 5 feet of the borehole should be filled with concrete to create a slab at least six inches thick above the borehole, with a diameter at least two feet greater than the protective casing. The concrete slab should be contoured to direct surface water runoff away from the wellhead.

4.3-5.3 Installation

4.3-5.3.1 Bentonite Pellets and Slurry

Properly installed, bentonite pellets and slurries provide a high density, flexible, low permeability seal. Bentonite pellets are preferred over cement grout for divider seals because they provide a solid seal where the continuity and thickness can be controlled by tamping and measurement. Bentonite pellets placed above the water table require that water be added, after the seal is in place, to activate the swelling of the pellets prior to installation of the annular seal. Bentonite slurries require set-up times of several hours before reliable measurements can be made. The use of bentonite seals on top of the filter pack also separates the well screen from the grout, and prevents the grout (a liquid when installed) from invading the filter pack. Separation of the filter pack from the grout is also desirable from a geochemical standpoint, to limit the effect of the grout on the pH of the well.

The methods of installing bentonite seals are similar to that of installing filter pack. Unless the hole is dry, the pellets should always remain below the bottom of the casing during installation.

This is necessary to avoid expansion and bridging of the pellets in the bottom of the casing. Bentonite slurry is placed through a tremie tube to the bottom of the casing prior to pulling the casing back.

It is strongly recommended that a bentonite pellet annular seal be tamped in place to assure that no voids occur and to help to remove any pellets that may adhere to the side of the casing. A tamping device can be fabricated from pieces of small diameter casing or from a small metal plate attached to a rod. The tamping device should have a half-moon or doughnut-shaped plate at the base with which to tamp the bentonite in place.

During installation, the depth to the top of the bentonite seal should be verified by measurement with a weighted tape or rod. Placing a small amount of sand or pea gravel on top of the pellets prior to making a measurement will help to keep the tape from sticking to the pellets.

As with filter pack, volume calculations should be prepared to estimate the amount of seal needed. Techniques similar to those employed in the calculation of filter pack volume can be used.

4.3-5.3.2 Grout Slurries

(a) Grout Pumps and Hoses

Grout pumps are used both to mix grout slurries and to pump them down the boreholes. Selection of an appropriate pump will ensure that the grout can be thoroughly mixed and rapidly emplaced. There are two basic types of pumps available for grouting: 1) variable displacement, and 2) positive displacement pumps. The basic differences between the pumps are briefly described below, as is their suitability for grout applications.

(1) Positive Displacement Pumps Positive displacement pumps maintain a constant output per revolution or stroke, regardless of the head that it is pumping against. Priming is not required with this type of pump. Common types of positive displacement pumps are rotary pumps, screw/worm pumps, and piston pumps. Example of these pump mechanisms are shown on Figure 4.3-4. Positive displacement pumps are better suited for pumping high viscosity fluids and, therefore, are excellent grout pumps. Due to their simpler mechanism, rotary pumps and screw/worm pumps are generally preferred over piston pumps for pumping grout.

(2) Variable Displacement Pumps   The output per revolution of variable displacement pumps varies with the pressure or elevation head. A variable displacement pump must be primed. A centrifugal pump is a common type of variable displacement pump. The single impeller, centrifugal pumps typically used in well drilling rely on suction lift as a driving force to maintain the prime during operation. The centrifugal pump is generally capable of suction lifts of 15 to 20 feet in water. In grout slurries this suction lift is even smaller, approximately 5 to 8 feet, due to the increased viscosity and weight of the grout.

(3) Pump Hoses Pump hoses should be of adequate size to handle the heavy, viscous grout. Generally 1- to 2-inch diameter discharge lines and 2- to 4-inch suction lines are used in well grouting operations. A common grouting problem is the potential for clogging of the lines or pump failure. If this occurs, the grout may harden in the pump, damaging or permanently destroying it. Consequently, pumps should be well maintained and frequently checked. Quick-connect couplings should be used on all pump lines to allow for rapid troubleshooting if problems occur.

(b) Grout Mixing

The importance of proper mixing of grout and water cannot be over-emphasized. The proper ratios of cement, bentonite or other additives, and water must be maintained in order for the grout to provide an effective seal. In general, grout is composed, by weight, of 20 parts of Portland cement for one part of bentonite, with a maximum of 8 gallons of water per 94-pound bag of cement. More bentonite may be required if the formation is very porous. In general, this ratio of cement to bentonite should not be less than 5:1. Only clean water should be used when mixing grout slurries; it is important to always mix the bentonite with the water first, before adding cement. Saline water or waters with a high mineral content can cause flash set of the cement (Gaber and Fisher, 1988) or flocculation of bentonite, destroying the integrity of the grout and, therefore, should not be used.

A mud scale is useful to monitor the density of the grout during mixing. The mud scale can be used to determine the density of the grout in pounds per gallon. Table 4.3-1 contains the recommended minimum densities for most common grout mixes. Several grout mixing methods are described below.

(1) Hand Mixing   Hand mixing is an acceptable method when small volumes of grout are needed (i.e., 5 sacks of cement or less). The water and dry powder are combined in a shallow tub or mud pit and mixed by hand using shovels, hoes or other implements. This method of mixing is labor-intensive and time-consuming. Smooth, good quality slurries are difficult to obtain with hand-mixed methods.

(2) Paddle Mixing Paddle-mixing incorporates the use of a barrel-shaped grout mixer. The slurry is mixed by paddles or blades that combine the water and cement by agitation, similar to the action of a blender. First, the appropriate amount of water is added to the tub and then the dry bentonite (if required) is added while the mixer is operating. Cement is then added to the slurry mixture. Mortar mixers are commonly used to prepare grout slurries. Standard mortar mixers can generally handle up to 3.5 cubic feet of grout. A standard mortar mixer can accept 2 or 3 bags of cement and 15 to 18 gallons of water for the appropriate mix ratio. A 94-pound bag of cement makes approximately one cubic foot of grout. Grout slurries can be mixed in batches and poured into a temporary holding tank until they are pumped down the borehole. Paddle mixers are suitable for mixing small to moderate quantities of grout, usually 20 bags or less. Figure 4.3-5 is an example of a paddle mixer.

(3) Recirculation Mixing Recirculation mixing is the most common method of grout mixing used by monitoring well contractors. Recirculation mixing involves combining the dry grout material and correct amount of water in a mud tub or half-barrel. The dry powder is mixed with water, using a high velocity fluid stream. A suction line is placed at one end of the tank and a discharge line at the other end. The fluid is continually recirculated through the pump and mixed at the discharge line until a smooth slurry is achieved. Pump lines should be equipped with a valve that allows the pump to be switched from recirculation to pumping without shutting the pump off. Figure 4.3-6 is a diagram of a recirculation mixing set-up.

(4) Jet Mixing Jet mixing is a technique primarily used for preparing bentonite muds for rotary drilling. Jet mixing operates with a high pressure inlet and discharge stream. The dry grout is added to a funnel located at the top of the inlet line, as shown on Figure 4.3-7. Due to the large amount of particle shear, jet mixing is not suitable for many bentonite-based grouts.

(c) Grout Placement Methods.

(1) Tremie Method In most cases the most acceptable method of grout installation is the tremie method. Grout is placed in the annular space from the bottom to the top by means of a tremie or grout pipe. The pipe is lowered to the required depth, slightly above the divider seal, and grout is pumped or poured down the tube. Grout is placed in the borehole in one continuous operation. The bottom of the grout pipe should remain submerged in the grout during the grouting operation and raised gradually. Grout should be pumped down the hole until grout of similar density discharges from the annular space at the ground surface. Once the grouting is completed, the pump and hoses should be flushed with clean water.

(2) Surface Pour Method   Pouring grout from the ground surface is acceptable in a very limited number of cases, such as when grout is installed in holes that are dry and less than 25 feet in depth. A pail or hose is used to introduce grout into the borehole and fill the annular space.

4.3-6 PROTECTIVE CASING AND SURFACE SEAL

4.3-6.1 General Considerations

The purpose of a protective well casing is to provide a water-tight, tamper-resistant sleeve around the monitoring well to protect it from accidental damage, infiltration, and vandalism. Protective well casings are generally constructed of steel or cast iron and have a locking cap, if possible. The two basic types of protective casings used in monitoring well installations are the above-ground casing and the flush-mount casing or road box.   For information on selection of the appropriate protective casing see Section 4.2 Selection of Well Materials.

Important elements in the installation of a protective casing are the inside diameter of the protective casing, the depth of the protective casing, and the installation of a concrete surface seal.

4.3-6.1.1 Protective Casing Diameter

The outside diameter of the protective casing should be sized to provide space for a sufficient surface seal (both horizontally and vertically). A protective casing 1 to 2 inches smaller than the borehole diameter is recommended. The inside diameter of the protective casing should be sufficiently large to permit easy removal of the riser cap for measurement and sampling activities. Protective casings with sharp edges may cut hands and damage cables, tubing and other equipment. These sharp edges should be filed smooth or covered with masking tape.

4.3-6.1.2 Depth of the Protective Casing

The protective casing should be placed at a sufficient depth to prevent frostheaving and to secure it in the ground. Generally depths of 3 to 5 feet below the ground surface are sufficient for placement of the base of the protective casing. The seal should generally extend up into the annulus between the protective casing and the well riser. This technique is used to keep water from accumulating in this portion of the annular space and causing damage from freezing. If this technique is used, a drain hole should be placed in the protective casing at the surface of the seal.

4.3-6.1.3 Surface Seal

A concrete surface seal should be installed around the protective casing. This will secure the casing in place. The seal should extend to the bottom of the protective casing and have a diameter at least 2 feet greater than the casing at the land surface.

4.3-6.2 Placement of the Protective Casing or Road Box

- During placement of the annular seal between the monitoring well and the borehole, terminate this seal where the base of the protective casing will be set.

- Prior to placing the protective casing in the borehole, be certain that the surface of the annular seal is sufficiently hard to support the protective casing. Adequate time must be allowed for the annular grout seal to set. If necessary, place a few inches of bentonite pellets and/or sand at the top of the annular seal. This will provide a firm surface on which to set the protective casing. The height of the protective casing should never be adjusted by twisting or hammering it into the annular seal.

- Slide the protective casing over the capped/vented monitoring well and into the borehole. Adjust the protective casing to the proper height above the riser cap (no less than 2 inches). A wooden block or other spacer placed between the well cap and top of the protective casing will allow for the proper separation to be maintained. This spacer will help to prevent settling of the protective casing while the grout is setting up. If necessary, add additional bentonite or sand to the borehole to obtain the proper protective casing height. Make certain that the protective casing is straight and that it is not interfering with the well riser.

- Place grout, generally consisting of concrete, around the protective casing or road box. If necessary, fill the annular space between the protective casing and the borehole with concrete grout.

4.3-6.3 Surface Seal

A concrete surface seal should be placed at the ground surface around the outside of the protective well casing. The seal should extend down around the protective casing for at least 3 to 5 feet. The pad, at least 2 feet in diameter around the protective casing, should form a cone-shaped collar around the casing, directing surface runoff away from the casing. Surface seals around road box protective installations may consist of cold patch asphalt.

4.3-6.4 Identification and Well Security

Once the installation is complete, the protective casing should be labeled and locked. Labels on the outside of the casing may include the owner or contact identification. The underside of the protective casing cover provides an ideal place for permanent identification markings, if the cover is permanently fastened to the protective casing. The unique identification number must always be placed on a part of the well that can never be confused with a part of another well. A reference point for water level measurements should be permanently marked on the well riser.

4.3-7 PROBLEMS AND POSSIBLE SOLUTIONS

4.3-7.1 Artesian Conditions

Flowing artesian conditions may prevent backfilling of the screen with sand or placement of the bentonite seals.

- In some instances, artesian conditions may only represent a few feet of elevation head above the ground surface. First try adding casing to the monitoring well to determine the elevation head. It may be feasible to add 5 to 10 feet of casing to the top so the elevation head can be established and the flow stopped. Once the flow has stopped, well construction can proceed.

- If the pressure is so high that it is not feasible to add additional casing, consider using a larger filter material that would fall through a water column despite upward gradients.

- A pneumatic multi-port monitoring system with inflatable packers (see Section 4.1) can be used in place of filter sand and bentonite seals.

- Pumping the newly installed well to temporarily stop the artesian flow may also facilitate installation of the filter pack, divider and annular seals.

4.3-7.2 Caving Conditions

Soil repeatedly caves in around the well screen when casing is pulled back during backfilling.

- o Add water to casing before and/or during retraction to create a positive hydraulic head.
- o Backfill within the casing only 4 to 6 inches at a time and pull casing back only that amount. This is possible even when working with casings with average sections of 5 feet or longer.
- o Determine if the geologic unit within which the screen is installed is suitable as filter material and, if suitable, allow caving to occur.

4.3-7.3 Filter Pack Bridging Between the Riser and Casing

Filter material becoming caught between the casing and the riser at a point above the screen.

- o Add water over the bridged area to settle the granular material to the bottom.
- o Wash out sand to bottom of casing sufficiently to free riser and start the process over.
- o Vibrate the riser by tapping or banging.
- o Remove riser from borehole, redrill boring to required depth, and start installation again.

4.3-7.4 Leakage through Road Box

Infiltration of surface water through the top of a flush-mount casing resulting in submergence of the monitoring well.

- o A double-pipe (manhole or sump pit) system, commonly used on underground gas tank fill pipes, can help prevent this from occurring.
- o A leak-proof cap or rubber gasket should be placed on the protective casing cover in flush installations to prevent water from ponding inside the protective casing.
- o Low areas subject to flooding or puddling should be avoided if possible. If flooding of puddling is suspected the flush-mounted protective casings can be slightly elevated to reduce the potential for surface water infiltration.

4.3-7.5 Settlement of Protective Casing

Settling of the protective casing over time, making it difficult or impossible to close the cap.

- o Care should be taken to ensure that the base of the protective casing is placed on a firm surface.

- o The use of a block or spacer placed between the top of the riser and inside of the protective casing cap during installation is recommended to minimize this problem.

- o In the flush installation, the well cap should be slightly recessed below the ground surface to ensure that vehicles or heavy machinery do not cause pressure directly on the well itself.

4.3-7.6 Heavy Traffic

In some heavily trafficked areas, the protective casing may not provide adequate protection from vehicles. Since the monitoring well represents a significant investment, additional posts or casings should be installed to provide a buffer zone for the well.

- o Three posts placed in a triangle, each about two feet from the well, should provide sufficient protection. Fewer may be adequate if the traffic pattern is well defined.

4.3-7.7 Winter Months

During winter months, short above-ground protective casings and flush (road box) installations may become obscured by snow and ice.

- o Where possible, install well-marked, brightly painted poles at the wellhead.

- o If flush installations are located in areas of traffic, nearby reference marks should be identified and clearly marked (flagged or painted) to aid in finding the wellhead.
- o Metal detectors are also useful in locating buried or obscured protective casings.

- o Hand-held torches help to loosen frozen locks and casings in non-explosive locations.

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ADDITIONAL REFERENCES

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SECTION 4.3
WELL INSTALLATION PROCEDURES

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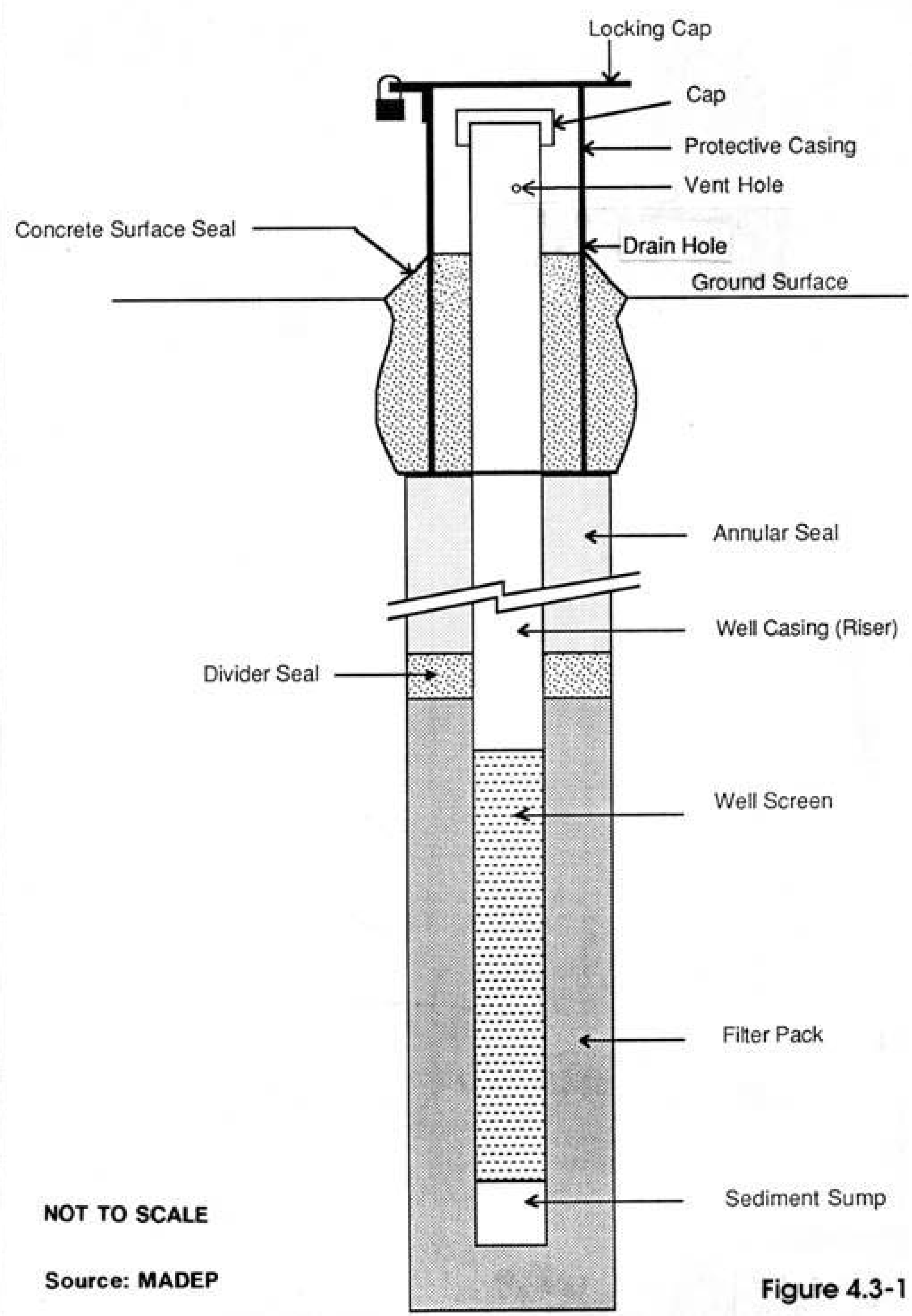


Figure 4.3-1

Well Component Diagram (Overburden).

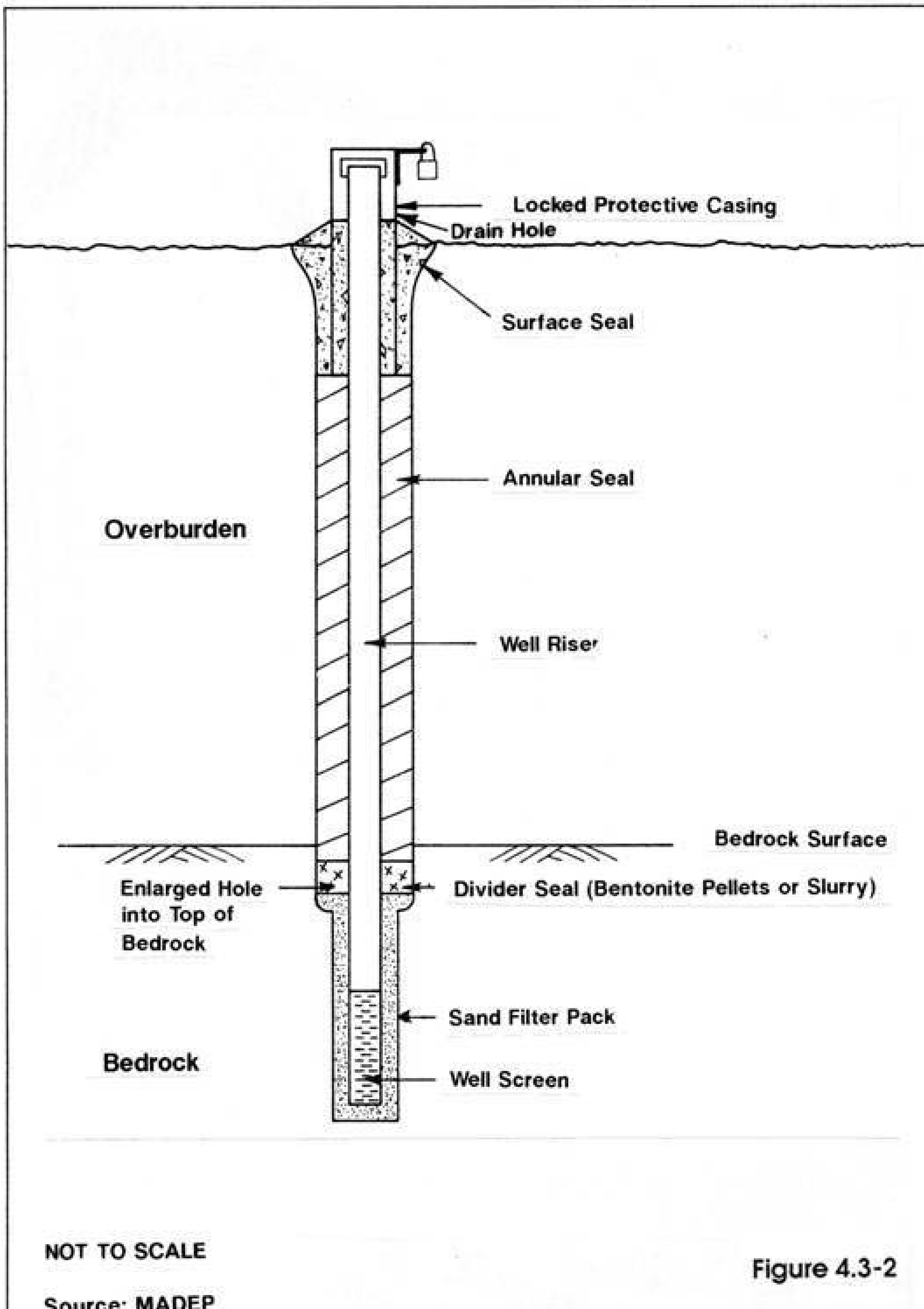
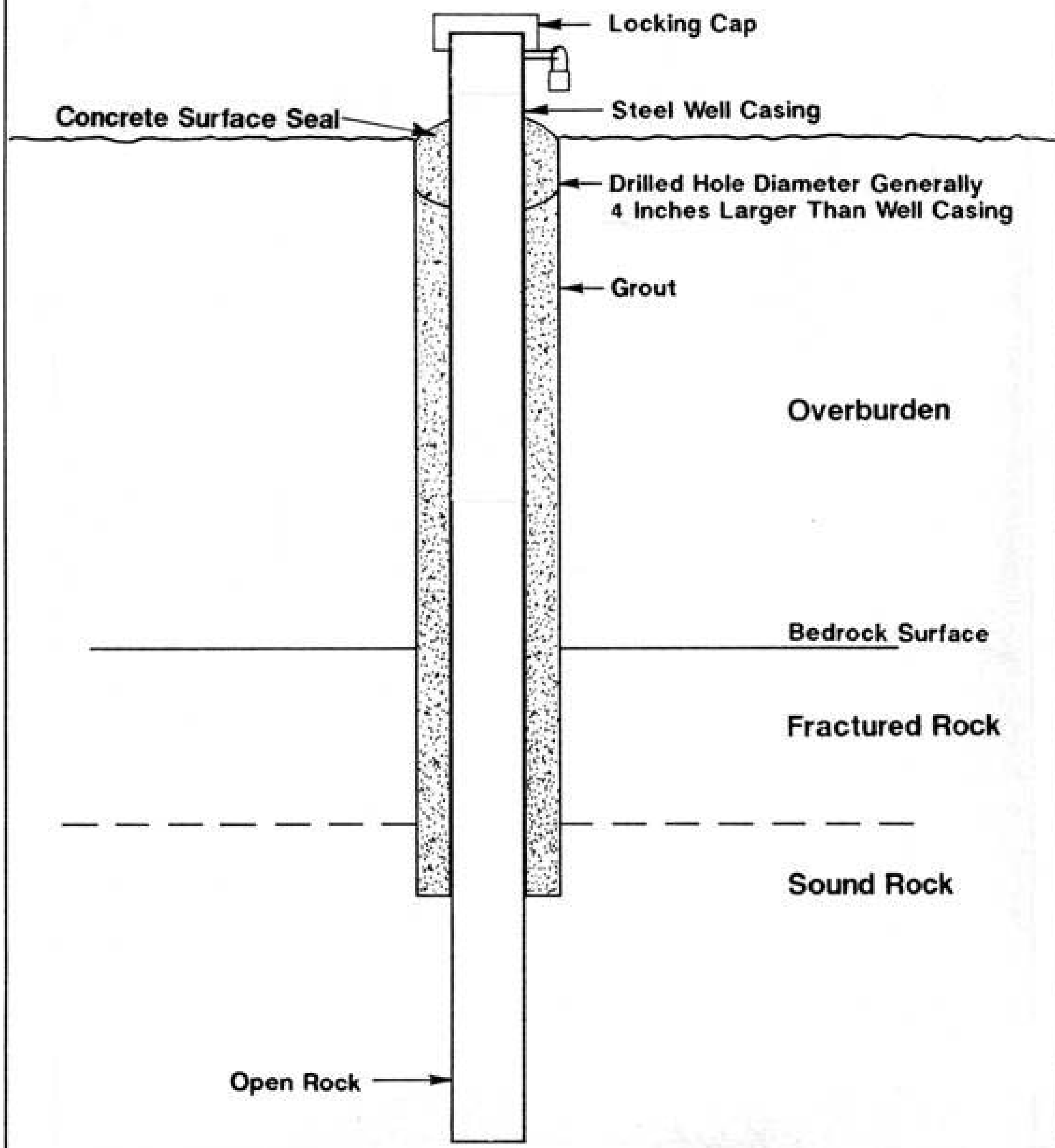


Figure 4.3-2

Well Component Diagram (Screen in Bedrock).



NOT TO SCALE

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Figure 4.3-3

Well Component Diagram (Open Hole in Bedrock).

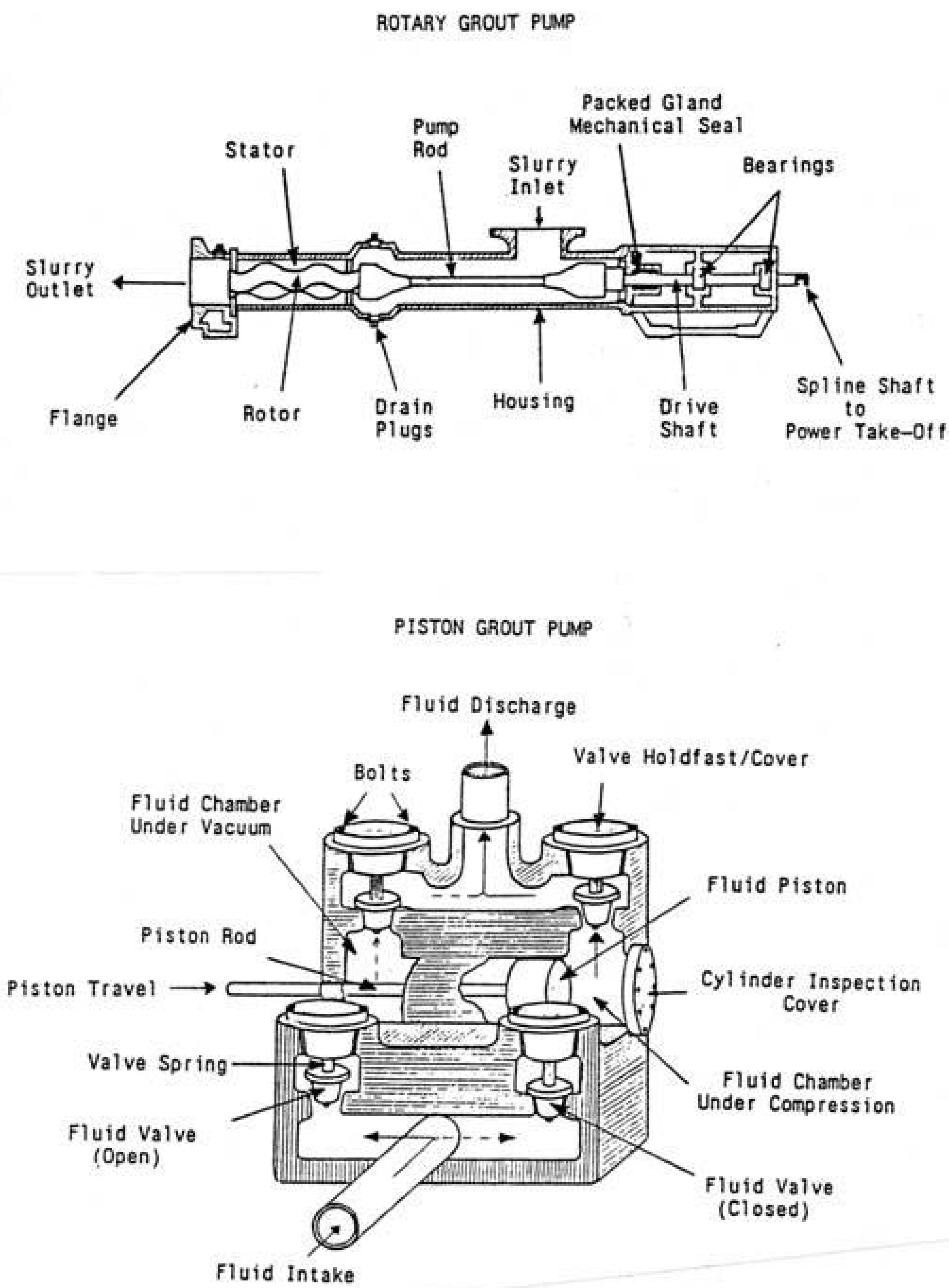
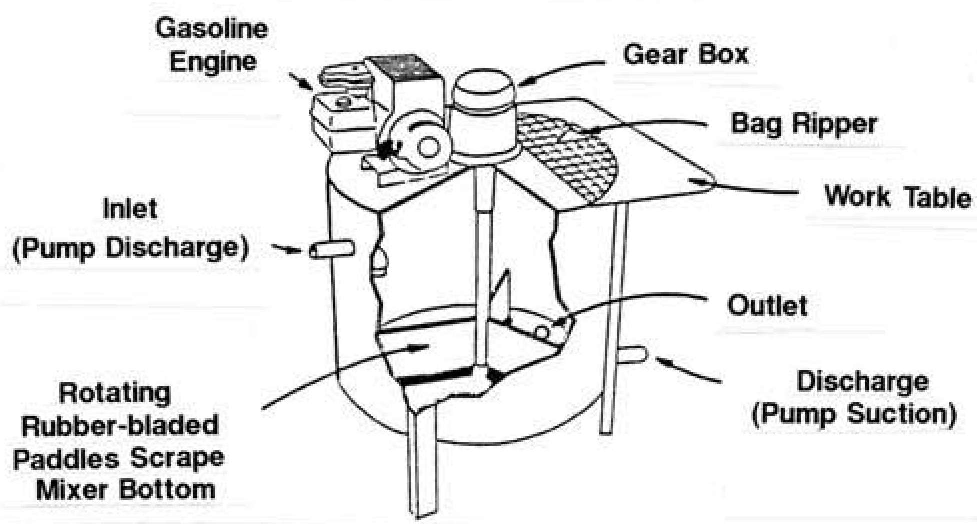


Figure 4.3-4

Source: Gaber and Fisher (1988)

Positive Displacement Pumps.



Source: Gaber and Fisher (1988)

Figure 4.3-5

Paddle Mixer.

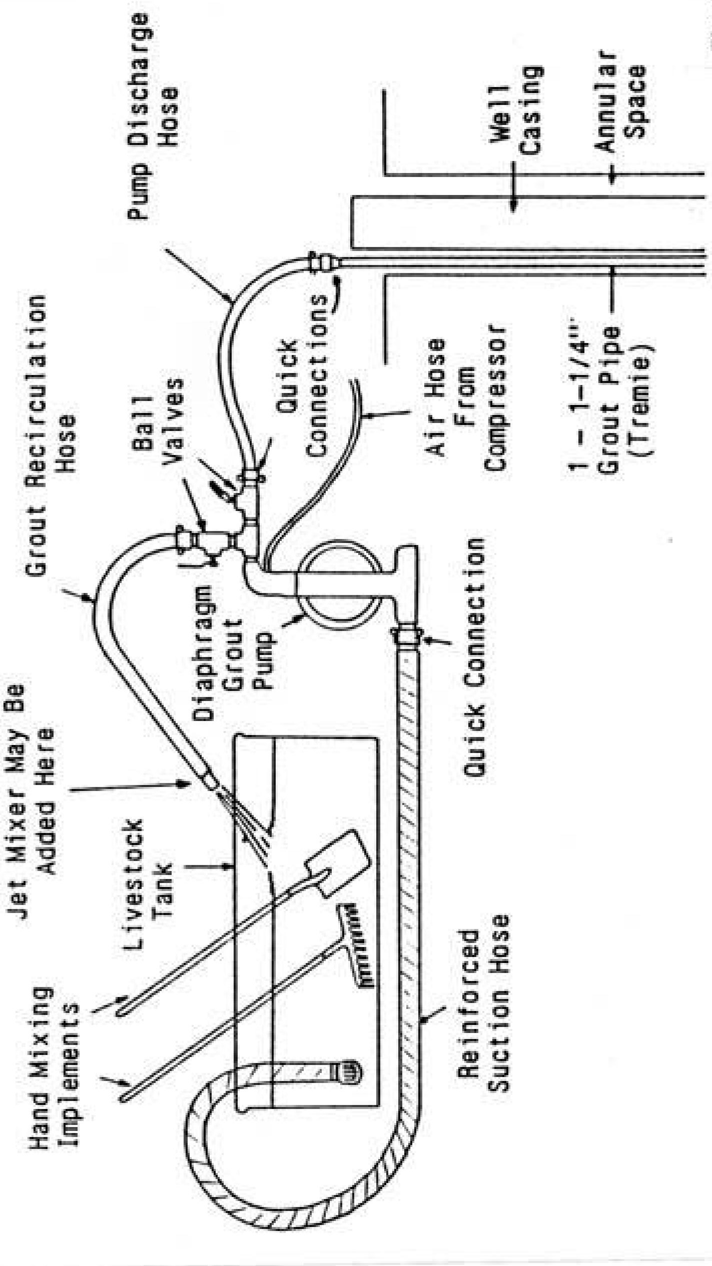


Figure 4.3-6
Diagram of A Recirculation Mixing Set Up.

Source: Gaber and Fisher (1988)

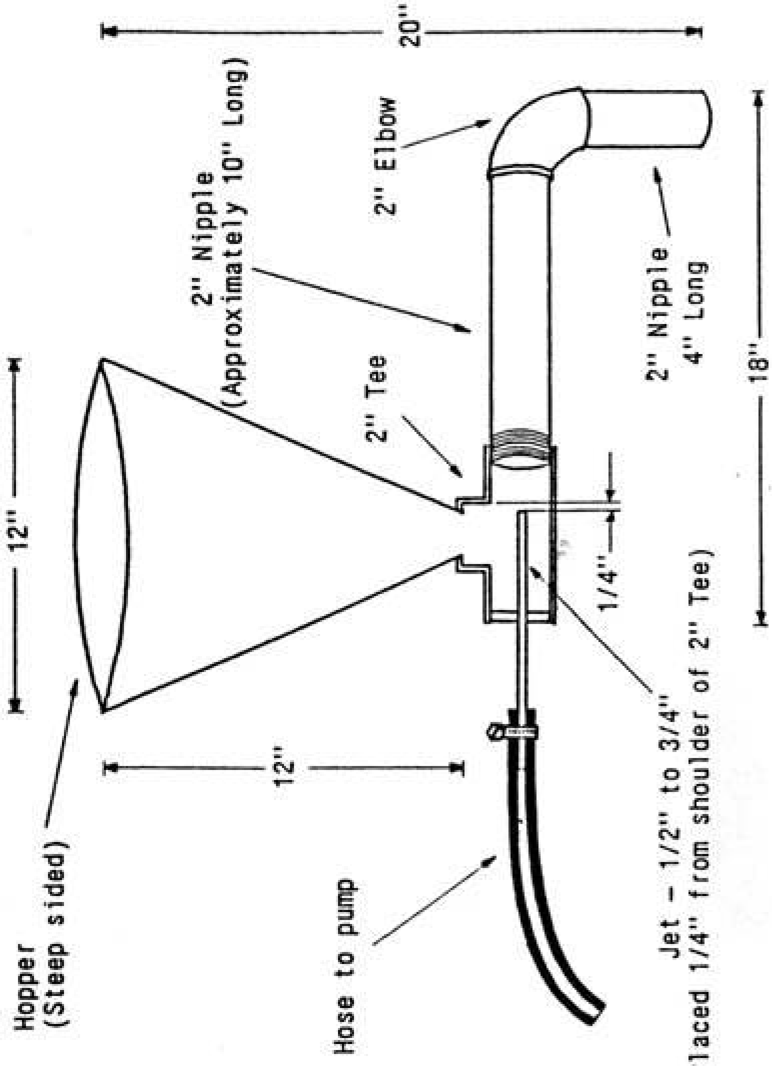


Figure 4.3-7
Jet Mixer Design.

Source: Gaber and Fisher (1988)

PRODUCT	WATER RATIO	MINIMUM DENSITY LBS./GAL.	VOL ft^3/sk
Neat Cement	6.0 gal./sack of cement 5.2 gal. recommended/sack of cement	15.0 15.6	1.28 1.18
Neat Cement & 1% Bentonite	6.0 gal./sack of cement	15.0	1.27
Neat Cement & 2% Bentonite	6.5 gal./sack of cement	14.7	1.36
Neat Cement & 3% Bentonite	7.2 gal./sack of cement	14.4	1.45
Neat Cement & 4% Bentonite	7.8 gal./sack of cement	14.1	1.55
Neat Cement & 5% Bentonite	8.5 gal./sack of cement	13.8	1.64
Neat Cement & CaCl (accelerator)	6.0 gal./sack of cement CaCl - 2 to 4 pounds/sack of cement	15.0	1.28
Concrete Grout	1 sack of cement and an equal volume of sand per 6 gallons maximum water	17.5	2.0
Bentonite Benseal/EZ-Mud	Benseal - 1.5 pounds/gallon of water EZ-Mud - 1 quart/100 gallons of water	9.25	4.75
Benseal/Quick-Gel	Benseal - 1.5 pounds/gallon of water Quick-Gel - 0.2 pounds/gallon of water	9.25	5.0
Volclay	2.1 pounds/gallon of water	9.4	3.6

Source: Gaber and Fisher (1988)

Table 4.3-1

Recommended Ratios for Most Common Grout Mixes

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 4.4 AS-BUILT NOTES AND RECORDS

SECTION 4.4
AS-BUILT NOTES AND RECORDS

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4.4 AS-BUILT NOTES AND RECORDS

4.4-1 PURPOSE

The purpose of an As-built Record is to compile permanent information about the actual location and construction of a specific monitoring well, including the subsurface geology at the well location. There are several reasons for submitting such information:

- To ensure that the minimum construction standards have been met, and that the installation is suitable for the site conditions.
- To provide an historical database of information on existing monitoring wells, subsurface materials, and water quality.
- To enable others to assess the integrity of the well installation so as to be able to evaluate the validity of the environmental data obtained from the well.
- To enlarge the database available from the centralized repository maintained by Water Resources Division of the Department of Environmental Management (WRD/DEM).
- To meet the requirements for well drillers by Massachusetts General Law Chapter 21 Section 16 and The Department of Environmental Management regulations 313 CMR 3.01(5).

4.4-2 METHODOLOGY

Ideally, the methodology used to achieve the purposes described above should provide a standardized format for evaluating monitoring well installations and for compiling the relevant information on a computerized database. It is possible to provide such information in either narrative or graphic format, or both. There are two key state agencies, the Department of Environmental Management (DEM) and the DEP, who are responsible for collecting such information.

The DEM regulates the drilling of wells and currently requires that well completion reports (including water and <u>monitoring</u> wells) be signed and submitted to DEM by a Massachusetts registered well driller (Figure 4.4-1). The person doing the actual drilling does not have to be registered. However, they must be supervised by a Massachusetts-registered driller.

The DEP regulates the installation of monitoring wells for protecting public water supply wells (Bureau of Resource Protection) and for waste site investigations and various permits (Bureau of Waste Site Clean Up and Bureau of Waste Prevention.)

The well completion reports required by the DEM for water wells is not sufficient for technical review of monitoring wells. For this reason the DEP has developed an As-built Form (Appendix A) and a boring log format (see Section 3.2) specific to monitoring wells. The information contained within them is considered essential for DEP technical review. Use of the formats is strongly recommended. However, they may be modified to fit specific needs. As-built and boring logs may be combined to provide graphic illustration of the well construction along side the boring log information. Include copies of as-built and boring log formats in the proposed work plan (Section 2.0). Appendix A also serves as an informational checklist for monitoring well installations. A schematic drawing of the installed well frequently serves to provide much of the same information that has been requested in narrative form. Examples of schematic drawings of As-built monitoring well forms are included as Figures 4.4-2 and 4.4-3.

4.4-3 EXAMPLES OF EXISTING AND PROPOSED WATER WELL COMPLETION FORMS

4.4-3.1 Well Completion Report Required by the Water Resources Commission

State Regulation 313 CMR 3.00 states, in part, that "Well drillers' reports will be submitted to the Water Resources Commission, Division of Water Resources, within thirty days of completion of any water well." 313 CMR 3.00 further states that:

> "Within thirty days after completion of any water well (productive or non-productive*), a registered well driller shall submit to the Water Resources Commission, Division of Water Resources, a report containing:
>
> (1) the name of the owner of the well;
>
> (2) the geographic location of the well (this shall be given accurately to enable easy plotting on a U.S. Geological Survey Topographic [1:25,000 scale] map);
>
> (3) well depth;
>
> (4) depth to bedrock or refusal;
>
> (5) casing type;
>
> (6) casing size and casing length;

(7) well screen type;

(8) well screen length;

(9) well screen depth set;

(10) static water level;

(11) method used to test well yield;

(12) length of time (in hours) that the well was pumped;

* "Non-productive Well" is defined in 313 CMR 3.00 as: A well which has been dug or drilled and sufficient water for its intended use is not available, or a well which has been dug or drilled for monitoring purposes.

(13) drawdown;

(14) well yield; and

(15) drilling logs describing the material and thickness penetrated.

Report forms will be issued by the Regulating Agency upon request."

A copy of the current DEM Water Well Completion Report is included in Figure 4.4-1. Their policy on monitoring wells is included in Appendix B.

4.4-3.2 Well Completion Report for Well Owner and Local Board of Health, Proposed by Division of Water Supply, DEP

In addition to the information required on the "Water Well Completion Report" form discussed above, it is recommended by DEP's Division of Water Supply that the following information be submitted to the well owner and, if required, the local Board of Health:

(1) The reference point for all depth measurements.

(2) The depth at which the first water was encountered.

(3) The composition and thickness of each stratum (clay, silt, sand and gravel, cemented formations, hard rock formations, etc.). Particle size, range and shape, along with rock type and smoothness, should be included. See Section 3.5, Soil Classification. Descriptions of materials should be made using the Udden-Wentworth scale or the USDA and Soil Sci. Soc. Amer. Scale. If another type of classification system is used, then this scale should be submitted with the report. Also, a Rock Quality Designation should be done in order to determine the fracturing extent of the bedrock if the private well is located in bedrock. See Section 3.7, Rock Classification.

(4) The depth interval from which each water and formation sample was taken.

(5) The depth at which the borehole diameter changes, if applicable.

(6) Any changes in Static Water Level with well depth.

(7) The number of feet drilled.

(8) The number of hours on the job.

(9) Any shutdowns that occurred due to equipment failure.

(10) Water level in the well at the beginning and end of each shift. In rotary drilling, the fluid level in the hole should be measured daily prior to starting pumps.

(11) Water level at each change of formation if readily measurable with the drilling method used.

(12) Any and all other pertinent information for a complete and accurate log (i.e., temperature, pH, and appearance [color] of any water samples taken).

(13) Depth or location of any lost drilling fluid, drilling materials, or tools.

(14) The depth of the surface or sanitary seal, if applicable.

(15) Total depth of completed well.

(16) The nominal hole diameter of the well bore above and below casing seal.

(17) The quantity of cement (i.e., number of sacks) installed for the seal, if applicable.

(18) The depth and description of the well casing.

(19) The description (to include length, diameter, slot sizes, materials, and manufacturer) and location of well screens, or number, size, and location of perforations.

(20) The sealing off of water-bearing strata, if any, and the exact location thereof.

(21) Records of well alignment and plumbness.

(22) Rate of Penetration Log: The rate of penetration into the formation should be recorded when drilling the hole. Types of bits used in addition to various weights applied on these bits, throughout the hole, should be submitted in this log. Any other information in regard to penetration rates should also be included."

4.4-3.3 Water Quality Report, Proposed by DEP's Division of Water Supply

It is recommended by DEP's Division of Water Supply that the local Board of Health require the well owner to submit to the Board a Water Quality Report any time a private water supply is tested. The report should include:

(1) who performed the sampling (i.e., the well owner, well owner's representative, BOH member, lab personnel);

(2) where in the system the sample was obtained (point-of-use or point-of-entry) and, if sampled at the point-of-use, whether or not the system was flushed prior to sampling;

(3) type of water treatment used (chemical or special device, if applicable);

(4) the time and date of sampling, of delivery to the laboratory, of extraction (or holding time - whichever is appropriate), and of sample analysis; and,

(5) a copy of the laboratory's test results.

Results that indicate no contamination are as important as those that indicate water quality problems because these results provide background data in case of future contamination. A complete record of all testing results is also useful when designing local water quality testing programs.

In these Standard References, this subject is more fully discussed in Section 6.0 Sampling and Analysis of Ground Water Samples.

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Well Location

Address ____________________

____

City/Town ____________________

Well owner ____________________

Address ____________________

____

Board of Helth permit: yes______ no ______

Geographical Description

______ (feet) N S E W of (circle)

______ (road)

______ (feet in tenths) N S E W of (circle)

intersect. w/ ______ (road)

Well Use

Domestic ______ Public ______ Industrial ______

Monitoring ______ Other ______

Method drilled ____________________

Date Drilled ____________________

Casing

Type ____________________

Length ______ ft. Dia (I.D.) ______ in.

Length into bedrock ______ ft.

Protective well seal:

Grout ______ Other ______

Well Data

Total well depth ______ ft.

Depth to bedrock ______ ft.

Water-bearing rock/unconsolidated material:

Description ______

Water-bearing zones:

1) From ______ To ______

2) From ______ To ______

3) From ______ To ______

Gravel pack well: dia. ______

Screen: dia. ______

Slot# ____ length ____ from ____ to ____

Well Test

Static water level below land surface ______ ft. Date ______

Drawdown ______ ft. after pumping ______ hr. ______ min. at ______ gpm

How measured ______ Recovery ______ ft. after ____ hr. ______ min.

Log of Formations

Materials	From	To

Comments

Driller ____________________

Mass. Registration# ____________________

Firm ____________________

Address ____________________

City/Town ____________________

____

Signature of supervising registered well driller

Office use only

Please print firmly

Driller Copy

Source: MA Department of Environmental Management

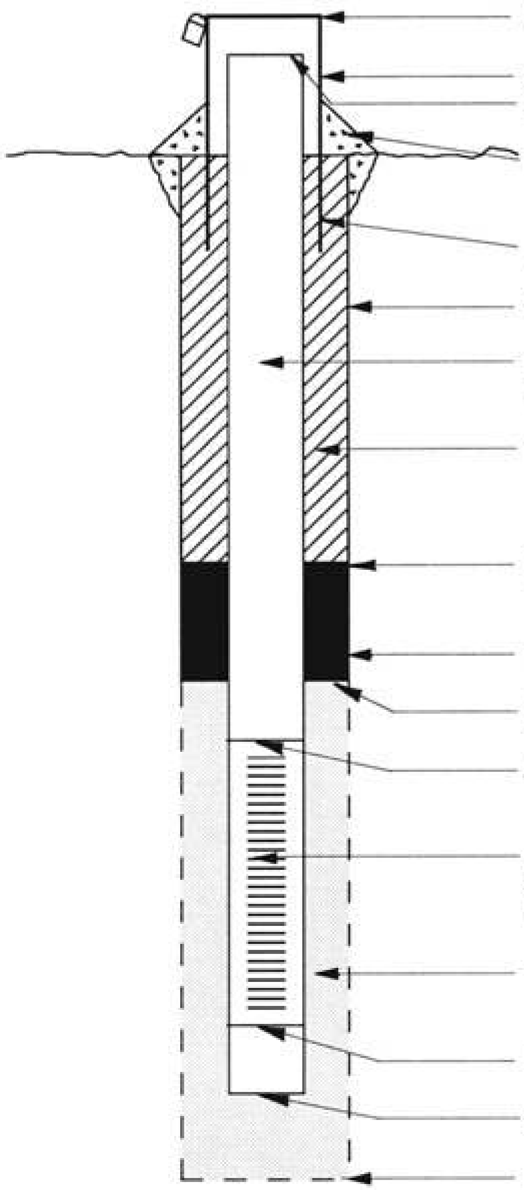
Figure 4.4-1

Water Well Completion Report Available from Department of Environmental Management, Division of Water Resources.

Project ____________________ Location ____________________ Driller ____________________

Project No. ________________ Boring ______________________ Drilling Method _______________

Elevation __________________ Date ________________________ Development Method ____________



Elevation of Top of Surface Casing: ________

Stick up of Casing Above Ground Surface: ________

Elevation Top of Riser: ________

Type of Surface Seal: ____________________

I.D. of Surface Casing: ____________________

Diameter of Hole: ____________________

Riser Pipe I.D.: ____________________

Type of Riser Pipe: ____________________

Type of Backfill: ____________________

Elevation/Depth Top of Seal: ________

Type of Seal: ____________________

Elevation/Depth Top of Sand: ____________________

Elevation/Depth Top of Screen: ____________________

Type of Screen: ____________________

Slot Size x Length: ____________________

I.D. Screen: ____________________

Type of Sand Pack: ____________________

Elevation/Depth Bottom of Screen: ________

Sediment Sump with Plug: ________

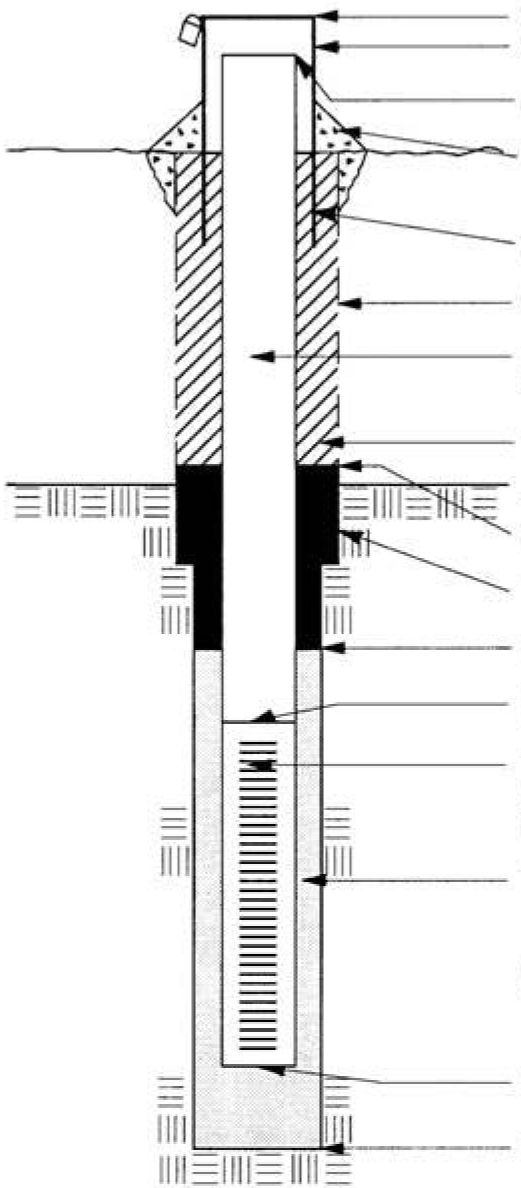
Elevation/Depth Bottom of Hole: ________

Source: MADEP

Figure 4.4-2

Example of an As-built Overburden Monitoring Well Form.

Project ________________ Location ________________ Driller ________________
Project No. ________________ Boring ________________ Drilling Method ________________
Elevation ________________ Date ________________ Development Method ________________



Elevation of Top of Surface Casing: ________
Stick up of Casing Above Ground Surface: ________
Elevation Top of Riser: ________
Type of Surface Seal: ________________
____
I.D. of Surface Casing: ________________
Diameter of Hole: ________________
Riser Pipe I.D.: ________________
Type of Riser Pipe: ________________
Type of Backfill: ________________
____
____
Elevation/Depth Top of Seal: ________
____
Type of Seal: ________________
Elevation/Depth Top of Sand: ________________
Elevation/Depth Top of Screen: ________________
Type of Screen: ________________
Slot Size x Length: ________________
I.D. Screen: ________________
Type of Sand Pack: ________________
____
Diameter of Hole in Bedrock:
Core/Rock: ________________
Elevation/Depth Bottom of Screen: ________
Elevation/Depth Bottom of Hole: ________

Source: MADEP

Figure 4.4-3

Example of an As-built Bedrock Monitoirng Well Form.

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APPENDIX A

A CHECKLIST FOR MONITORING WELL INSTALLATION AND AS-BUILT FORM

APPENDIX A

A CHECK LIST AND AS-BUILT FORM FOR MONITORING WELL INSTALLATION

1. Monitoring Well I.D. Number

   I.D. Number ______________________________

2. Property Owner

   Name:

   Address: ______________________________
   ____
   ____

   Telephone No.: ______________________________

   Contact ______________________________

3. Individuals Involved in Installation

   Name of Drilling
   Contractor Firm: ______________________________

   Address: ______________________________

   ____

   Name of Driller: ______________________________

   Name of
   Consultant Firm: ______________________________

   Address: ______________________________

   ____

   Name of Inspector ______________________________

4. Date Installed

Date:

5. Location

Town:

Plot Plan Number:____

NOTE: A copy of the plot plan map showing the well locations and well ID numbers must be submitted with this form.

Name of Surveyor: ____

Address: ____

___ ____

C.E. Reg. No.:___________ or RLS Reg. No. ___________________

Coordinates (check one):

Latitude and Longitude _________ UTM Grid ___________________

N-S line:

E-W line:

6. Elevation

NOTE: All elevations must be provided as feet above Mean Sea Level (MSL)

Reference Datum:____

Vertical Accuracy:____

Elevation, Top of Riser, uncapped _____________________________feet

Elevation, Ground Surface:__________________________________feet

Name of Surveyor: ____

Address: ____

____ ____

C.E. Reg. No.:___________ or RLS Reg. No.: ________________________

7. Drilling Information

Drilling Method:____

_

Borehole Diameter:____inches

Water source used:____

Water quality tested: yes____________ no _______________________

Criteria for refusal: ___________________________number of blow counts

8. Geology

(a) Soil

Sampling interval:__________________________________

(b) Rock

Depth to
top of rock: feet below ground surface

(c) Aquifer Tests

Type _

Hydraulic conductivity _____________________________________

Method of Analysis ____

9. Well Installation Details

Single-level well_________ or Multi-level well ______________

NOTE: Complete sections (a) through (e) for each separate monitoring zone in multi-level well installations.

(a) Riser pipe

I.D. ___________inches

Material

Stickup Length ____feet
or
Stickdown Length_ ______________________________________feet

Total Length of Riser Pipe _______________________________feet

(b) Well screen

I.D. __________inches

Length_ feet

Screen Type ____

Slot Size ____

Sediment Trap yes ________ no _________
if "yes," how long is the sediment trap? __________________ inches

(c) Filter pack

Quantity ____ cubic feet

Material Description _____________________________________

____

(d) Divider seal

Bentonite pellets placed above the filter pack?

yes_________ no___________

Depth of seal below land surface:

From ______ to _______ feet

Method of placement ____________________________________

____

(e) Annular seal

Type of grout slurry used _________________________________

Mix ratio

Method of Placement_ ____

Volume_______________gallons

Depth below Land Surface: From _____ to _____feet

(f) Surface seal

Type:

Mix ratio:

Depth below Land Surface: From ______ to _____ feet

Apron: Diameter:____________________________feet

Thickness:_________________________inches

Protective casing yes ____________ no ___________
or
Road box yes ____________ no ___________

Material: ____

Length: ____feet

I.D.: ____inches

10. Well Development

Method:____

Amount removed: _______ gallons or duration _______ hours

Quality of water after development__________________________________

11. Signature Block

Prepared by:____________________________ Date _________________
(Driller or Inspector)

Submitted by:____________________________ Date _________________
(Consultant)

Property Owner:__________________________ Date _________________

APPENDIX B

REVIEW OF REQUIREMENTS FOR REGISTRATION AND WELL COMPLETION REPORTS; DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

Commonwealth of Massachusetts
Executive Office of Environmental Affairs
Department of Environmental Management

M E M O R A N D U M

100 Cambridge Street
Boston
Massachusetts
02202

Division of Water Resources

TO: Monitoring Well Drillers

FROM: Richard H. Thibedeau, Director
Division of Water Resources

DATE: March 12, 1990

SUBJECT: Review of Requirements for Registration and Well Completion Reports

We have received a number of questions regarding state requirements for monitoring well drillers on registration and submittal of well completion reports. In response, we have reviewed the state's administration of these requirements, and have assembled the following guidelines to assist monitoring well drillers in meeting these requirements.

1. Confidentiality of Owner

GUIDELINE: IF THE OWNER IS UNKNOWN, OR IF THIS INFORMATION IS CONFIDENTIAL, SUBSTITUTE THE CLIENT'S NAME AND ADDRESS ON THE WELL COMPLETION REPORT. WRITE "CLIENT" OVER THE WORDS "WELL OWNER".

Background: Some monitoring well drillers are experiencing difficulty complying with the requirement of furnishing the well owner's name and address, as this information may not be readily available to the driller.

The Division has the responsibility of providing a publicly-accessible data base on all wells in the state, and well reports are retrieved by using well location, name of owner, or date well was drilled. For monitoring wells, the Division's responsibility can be confined to well location, and to general well data which relates to the water table and groundwater aquifers. Since the Division is not the repository for detailed information regarding the specific purpose of monitoring wells, the Division can use the client's name as a referral, should more detailed information be requested.

2. <u>Number of Well Completion Reports Per Site</u>

GUIDELINE: SUBMIT ONLY ONE WELL COMPLETION REPORT FOR A SITE WHERE MULTIPLE NUMBER OF MONITORING WELLS ARE DRILLED, IF THE WELLS ARE IN REASONABLE PROXIMITY TO EACH OTHER, AND THE SUBSURFACE CHARACTERISTICS ARE SIMILAR. PROVIDE WELL DATA FOR THE DEEPEST WELL. MAKE NOTE ADJACENT TO "WELL LOCATION" AT TOP OF WELL COMPLETION REPORT OF NUMBER OF WELLS DRILLED.

<u>Background</u> To meet its responsibility under Law, the Division needs to maintain records which show where monitoring wells are drilled amd at what point they intercept the water table. Multiple wells on a site which are shallow in depth and are used for observation purposes, are usually similar in physical characteristics. The Division's responsibility is met if the report on file provides characteristic information for these multiple wells, and identifies the number of monitoring wells constructed at the site.

3. <u>Data Required on Well Completion Report</u>

GUIDELINE: SUBMIT DATA REQUESTED UNDER REPORT HEADINGS OF WELL LOCATION, GEOGRAPHIC DESCRIPTION, WELL USE, METHOD AND DATE DRILLED, CASING, WELL DATA, LOG OF FORMATIONS, AND DRILLER INFORMATION. UNDER "PUMP TEST", FILL IN ONLY "STATIC WATER LEVEL" AND "DATE".

<u>Background</u> The Division's records are required to show where wells were drilled, both productive and nonproductive, and where they intercept the water table. The data required from a monitoring well driller is to be consistent with general information required of all wells for public health and environmental purposes, and includes location, well type, and characteristics related to water table intrusion.

4. <u>State Qualification Requirements for Monitoring Well Driller Registration</u>

GUIDELINE: EXISTING QUALIFICATION REQUIREMENTS ARE MINIMUM FOR REGISTRATION PURPOSES. NEITHER GRANDFATHERING CONSIDERATIONS NOR TEMPORARY CERTIFICATES ARE APPLICABLE.

<u>Background</u> State law MGL *c.* 21 *s.* 16 makes no distinction concerning types of wells or qualifications needed to drill these wells. The law requires that persons engaged in the business of drilling <u>all</u> types of wells must be registered, and that administrative regulations to implement this law are to be promulgated by the Division of Water Resources. The Division's policy on implementing this law has been to focus on the law's interface with other related state laws. In this regard, the Division has promulgated regulations designed to assure the public that well drillers have attained a level of drilling competence which is regarded as minimal for supervising a drilling operation, with full regard for environmental, health, and public safety factors.

The qualifications selected by the State as minimal for monitoring well driller are endorsed by the well drilling industry (National Water Well Association in attached article). Grandfathering by the state was allowed only in 1981 when regulations were altered significantly to conform with industry standards; no public interest would be served in reinstituting such a provision. The temporary certificate provision has been retained in the regulations since 1981 for the sole purpose of administering reciprocity with other comparable states.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 4.5 WELL DEVELOPMENT

SECTION 4.5
WELL DEVELOPMENT

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4.5 WELL DEVELOPMENT

4.5-1 PURPOSE

Well development is a necessary step in the completion of most ground water monitoring well installations. Development of a monitoring well helps to remove sediment and enhance the hydraulic connection between the well and the aquifer. Regardless of the drilling method used in the installation of a monitoring well, all methods cause some alteration or rearrangement of the fill or natural soil or rock material in which the well screen is placed. Since monitoring wells are installed to collect physical and chemical data indicative of in-situ aquifer conditions, the methods of drilling and installing wells should minimize the disturbance of aquifer materials that adversely impact the quality of the data collected. Wells not intended for sampling, such as piezometers and observation wells, may not require development.

The objective of well development is to enhance the hydraulic connection between the well screen and the natural formation or fill by removing fine soil material or drill cuttings and subsequently rearranging the natural or artificial sand filter pack around the well. Well development may increase the hydraulic conductivity in the vicinity of the well screen. This should be considered when in-situ hydraulic conductivity tests are planned. Appropriate mechanical rearrangement of the sand or gravel pack (i.e., development) will allow the ground water to move through the sand pack more easily and reduce the amount of fines that enter the well. Since ground water in most New England aquifers travels at velocities too low to retain suspended material, any turbidity associated with monitoring wells is likely to be an artifact of the well installation process. Well development can reduce this turbidity and, therefore, reduce the chance of chemical alteration of ground water samples caused by suspended sediments. In addition, it can remove fluids introduced during drilling or installation. In this discussion, well development involves preparation of the well for collection of hydrologic and chemical data. If samples are collected for chemical analysis, the well must be purged prior to sample collection (see Section 6.0).

Frequently, inadequate consideration is given to the selection of appropriate well development techniques and duration of development, compared with the time spent on selection of well materials or sampling protocols. In order to obtain hydrologic and chemical data that is representative of the pre-drilling site, the hydrologic conditions in the vicinity of the well screen should be restored to their natural state as much as possible. Additionally, consideration must be given to the amount of drilling water or fluid that was introduced into the aquifer during drilling. If ground water flow velocities are low it may be desirable to remove the added drilling water in order to obtain representative samples for chemical analysis.

Care should be taken during well development to avoid entrapping air in the formation or plugging well screens with fines. If additional clean water is introduced during development, care should be taken to make certain that the amount of water removed exceeds the amount that has been added.

The use of development methods that introduce additional water into the formation or that cause significant alteration of the natural materials in the vicinity of the screen may be undesirable for some ground water monitoring applications, such as highly contaminated aquifers. If additional water is introduced during development to flush the screen, this volume of water must be removed as part of the development process and may require storage and disposal as a hazardous waste.

In choosing a well development method, the purpose of the well must be considered. Wells used primarily for potentiometric head information can be developed by the introduction of clean water, since the addition of water will not jeopardize the validity of water level data. However, if the primary purpose of the monitoring well is to provide data on groundwater chemistry, the effects of the development method on the contaminants and natural geochemistry must be considered.

The purposes of well development are:

- to remove fluids introduced during drilling or installation.

- to reduce the amount of fine grained material entering the well from the surrounding formation

The following section on development methodology will specifically address the development techniques most widely used for monitoring wells. There are other techniques that are used for development of water supply wells, but they may not be applicable for developing monitoring wells. The methods described are not necessarily appropriate for all monitoring wells. Aquifer conditions and constraints, especially permeability and depth to the water table, will dictate the specific applicability of any of these methods. It is expected that variations and combinations of these methods will probably be required at some sites. It should be noted that all equipment placed in a monitoring well for development, purging or sampling should be decontaminated. Decontamination methods are presented in sections 6.5 and 3.3 of the Standard Reference Document.

4.5-2 METHODOLOGY

Well development can be performed using a variety of methods and equipment. The specific method chosen for development of any given well is governed by the purpose of the well, well diameter and material, depth, accessibility, geologic conditions, static water level in the well, and the type of contaminants present, if any. Any of the development methods discussed in this section can result in overdevelopment. Monitoring wells should be developed only to the point that enables them to function for their intended purpose. The most technically feasible and commonly used methods for developing monitoring wells include:

- Over-pumping
- Backwashing (or rawhiding)
- Mechanical surging
- Air-lift pumping
- Water jetting

Bailing is a technique that is not generally recommended for well development, because it is slow and not effective in adequately removing suspended sediment. Bailing is generally used for ground water sampling and sometimes for purging wells prior to sampling.

4.5-2.1 Over-pumping

Over-pumping a well involves pumping at a faster rate than the well would normally be pumped or purged for sample collection. This is one of the easiest and most common methods of well development.

Theoretically, overpumping increases the hydraulic gradient near the well by drawing the water level down to as low a level as possible. The steepened hydraulic gradient increases the velocity of the ground water moving through the screen into the well. The increased velocity will move residual fine soil or rock particles into the well and clear the well screen of this material. Care must be taken not to entrap air into the formation around the screen during development. This can be prevented by not lowering the water level outside the well below the bentonite/cement seal.

This method of over-pumping is best suited to aquifers comprised of sands and gravels or high-yielding consolidated rock with shallow water tables. The suction line, pump, or bailer is lowered into the well and water is removed. If the permeability of the formation is sufficiently high, repositioning of the pump or line intake within the screen may be required to pull material into the well along the entire length of the screen.

Typical problems encountered using this method are the lack of effective pumping devices that will fit within a 2-inch diameter monitoring well and produce satisfactory pumping rates. Above-ground peristaltic/centrifugal pumps are effective when the water level is within 15 to 20 feet of the ground surface. If the ground water contains hazardous constituents, pumping large volumes of contaminated water may pose disposal problems.

4.5-2.1.1 Advantages and Disadvantages

(a) Advantages

- o Useful in wells with shallow water-levels (less than 25 feet deep) where a suction line can be used.
- o Relatively simple procedure.
- o Most drill rigs will have the capability of pumping at a high rate at depths of 10 to 15 feet or less.

(b) Disadvantages

- o If the permeability is quite high or quite variable, only a section of the screened zone may actually be developed, especially in wells with long screens.

- o Over-pumping may compact finer sediments around borehole and screen, restricting groundwater flow into the screen If this happens it may be very difficult to correct.

- o May result in an unstable formation around the well screen (i.e., bridging of fines may allow formation of voids around coarser-grained material).

- o At contaminated sites over-pumping may produce a large volume of contaminated discharge water that must be disposed of as a hazardous waste.

4.5-2.2 Backwashing (Rawhiding)

Unfortunately, overpumping alone may not adequately develop most monitoring wells. Pulling water toward the screen without some return of water into the formation may result in bridging of the soil or rock particles around the screen. This bridging may continue until the pumping is stopped. Once pumping has stopped, the flow may reverse and unseat the bridged particles. The fines may re-enter and settle into the well until the next time it is pumped. A modification to the over-pumping technique that increases the effectiveness of development is called surging and pumping, rawhiding or backwashing.

In this method a pump is used to lower the water level in the well, thereby increasing the ground water velocity entering the screen. However, after drawdown is achieved, the pump is turned off and the water in the pump discharge line is allowed to re-enter the well. This reversal of flow through the screen will help prevent bridging and reduce the suspended fines that may re-enter the well screen. The equipment used for this method is the same as in over-pumping with similar operational techniques. A problem with this method is that it tends to develop the most permeable zones within the screened portion of the well. This method should be used with caution in wells intended for sampling because it introduces and recycles water into the formation. In order to ensure that representative water samples are collected, more water should be withdrawn from the formation than is introduced. Surging and pumping may be the most appropriate technique if short well screens (e.g., 5-foot or less) are installed in relatively homogeneous aquifer materials. Because the geology is relatively uniform, this technique will develop the entire monitored zone.

4.5-2.2.1 Advantages and Disadvantages

(a) Advantages

- Will help reduce bridging of fines around the well screen.
- Effective for short screens (5-foot or less) located in homogenous aquifers.

(b) Disadvantages

- May overdevelop the more permeable zones, leaving a portion of the well undeveloped.
- If the screened zone is highly contaminated, backwashing may cause mixing of the contaminants.

4.5-2.3 Mechanical Surging

Another method occasionally used to develop monitoring wells is surging. This technique employs a tool called a surge block, commonly found on a cable tool rig. This device first forces water within the well through the well screen and out into the formation, and then pulls water back through the screen into the well along with fine soil or rock particles. Surge blocks are usually fabricated for specific well applications. A typical surge block construction detail and application is shown in Figures 4.5-1 and 4.5-2.

The surge block is typically attached to a drill rod, drill stem, or line that has sufficient weight to allow the surge block to rapidly drop through the water column. The surging action should start at a slow pace, near the water level within the well and progress to a faster pace near the well screen. Surging action can be carried out within the well screen if adequate measures are taken to clean out accumulated silt or material prior to surging. Otherwise, the fines may be forced out through the well screen into the surrounding filter pack. Accumulated material may also bind or lock the surge block in place if precleaning is not performed. Periodic bailing or pumping of the soil or rock particles is necessary regardless of the location of the surging within the well.

A typical surge block has approximately 1/4-inch clearance between the flexible leather or rubber discs and the inside of the well casing. Violent or too rapid surging in a well situated in a low permeability formation may damage the well. Variations in surge block construction involve the addition of flap valves to allow some water and silts to pass through the block rather than between the block and wall of the well. Additionally, check valves can be added to the surge block to allow removal of development water and associated silts. After surging, additional development can be performed, if desired, using the rawhiding or backflushing techniques previously described.

4.5-2.3.1 Advantages and Disadvantages

(a) Advantages

- Gentle surging combined with gentle pumping through the center of the surge block has been very successful for development in formations containing a considerable amount of fine material.

- Inexpensive and relatively simple tool.

- Effective in wells installed in highly permeable homogenous formations.
- Does not require the addition or withdrawal of substantial volumes of discharge water except for flushing.

(b) Disadvantages

- Vigorous surging may damage non-metallic well screens.

- May cause the formation around the screen to become clogged by pushing fines back into the formation, reducing flow into the well.

- If the surge block fits too tightly into the well casing, the surge block can damage the well screen.

- May remove sufficient formation material outside and above the well screen causing the seal to collapse, resulting in infiltration of overlying aquifer material.

4.5-2.4 Air-surging and Air-lift Pumping

Air development involves the use of air pressure to remove water from a well. Two basic techniques are air-surging and air-lift pumping.

4.5-2.4.1 Air-surging

Although air-surging is described, it is not recommended for monitoring well development. In air-surging development, compressed air is blown into the well to force water and soil or rock particles out of the well under pressure. This technique removes soil or rock accumulations from a well but has the potential to trap air in the formation pore spaces or fractures. If air is entrapped it may inhibit the flow of ground water into the well.

4.5-2.4.2 Air-lift Pumping

Air-lift pumping is similar to air-surging but this technique does not allow air to pass through the well screen. With this technique compressed air is introduced into the well through a small tube in the base of an eductor pipe that has been lowered to the base of the well. The air displaces the water in the eductor tube, causing the water to flow into the eductor tube and be discharged at the surface.

For development by this method to be successful, it is necessary to have a ratio of submergence of at least 60 percent. That is, the water must rise high enough in the well so that it is possible to have 60 percent of the airline and eductor hose in the well under water. The distance the line is under water should be divided by the total length of line in the well, and then multiplied by 100. This will yield the percentage of submergence. For example, if a 170-foot airline is under water 110 feet, the submergence is calculated as follows:

$$\frac{110}{170} \times 100 = 0.647 \times 100 = 64.7\%$$

A typical air-lift system consists of two small-diameter tubes: one is a small tube attached to an air compressor and the other larger tube acts as the water discharge. The air tube is attached to the eductor tube and terminates inside and facing upward within the eductor tube (see Figure 4.5-3). Portable air compressors with a range from 40 to 100 psi at 5 to 15 cfm are typically used for well development. If possible, an oil-less compressor should be used; otherwise a hydrocarbon filter should be attached to the discharge line on the air compressor to filter out any airborne oils produced by the compressor. Compressed air is slowly added to the system until water and silt flow out of the discharge tube. Use of nitrogen gas, rather than compressed air, may be desirable because accidental introduction of nitrogen gas into the well is less likely to affect the water quality than the compressed air.

This development method is similar in function to the over-pumping technique discussed in Section 4.5-2.1. The advantage of the air-lift system is that wells with very deep static water levels or wells installed in silty aquifer materials can be easily developed. This system can be built to fit within a 2-inch diameter well; it is easily installed and operated. However, air-lift pumping without backflushing still creates the potential for bridging around the screen. A combination of air-lift pumping with backflushing should result in effective development of most monitoring wells. This method can be conveniently performed by first pumping and then shutting off the air to allow the rising water column to fall back down the discharge pipe. As with any development system, extreme care should be taken not to introduce air or highly aerated water into the formation as this may alter the water quality, permeability and geochemistry in the vicinity of the well.

(a) Advantages and Disadvantages

(1) Advantages

- o Effective in wells with deep static water levels and in wells containing a lot of clays and silts
- o Effective in small diameter wells.
- o Capability to pump and surge without removing the equipment.
- o A drill rig is not required for this method.
- o Can control pumping rate by controlling air-flow.

(2) Disadvantages

- o May force air into the formation, which may lead to air locking of the formation, affecting permeability, water quality and the flow of water to the well.
- o Generally, only low flow rates (e.g., 1 to 2 gpm) are possible.
- o May not be effective in wells with less than 30- or 40-feet of standing water.

4.5-2.5 Water Jetting

High velocity water jetting is a rarely used but effective technique for development of wells installed in highly permeable aquifers. Jetting consists of the discharge around the well screen of horizontal jets of water under high pressure. The water jets act to dislodge soil or rock particles near the well screen and break up any dense soil or filter cake caused by mud rotary or auger drilling. Both auguring and mud rotary drilling methods tend to develop a filter cake or dense soil or rock layer on the borehole wall. Unless removed, this layer can alter the natural permeability of the aquifer. In order to be effective in developing the well, water jetting must be accompanied by pumping or air-lifting to remove the fines. Again, this development method should be used with caution to avoid damaging the screen or developing voids in the filter pack surrounding the screen.

4.5-2.5.1 Advantages and Disadvantages

(a) Advantages

- o Effective in highly stratified, unconsolidated formations.
- o Can be accomplished with most drill rigs.
- o Entire section of screened zoned can be developed.

(b) Disadvantages

- Introduces water into the formation.
- Requires equipment that may not fit into a 2-inch diameter well.
- More time-consuming than other methods.

REFERENCES

Driscoll, F.G., 1986, Groundwater and wells: St. Paul, MN, Johnson Division, UOP, Inc., 1089p.

SECTION 4.5
WELL DEVELOPMENT

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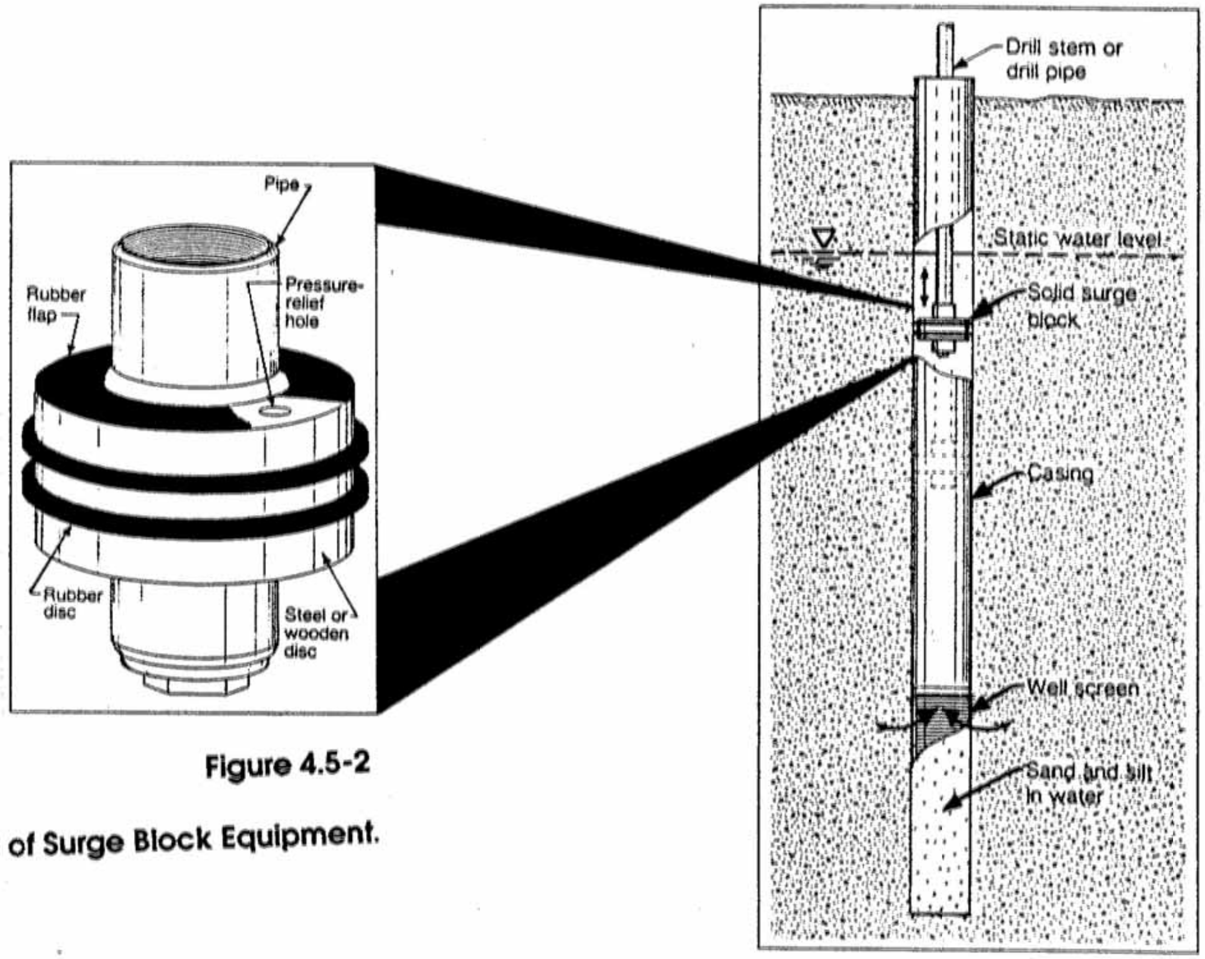

Figure 4.5-2

Detail of Surge Block Equipment.

Figure 4.5-1

Operation of a Surge Block System.

SOURCE: Driscoll (1986)

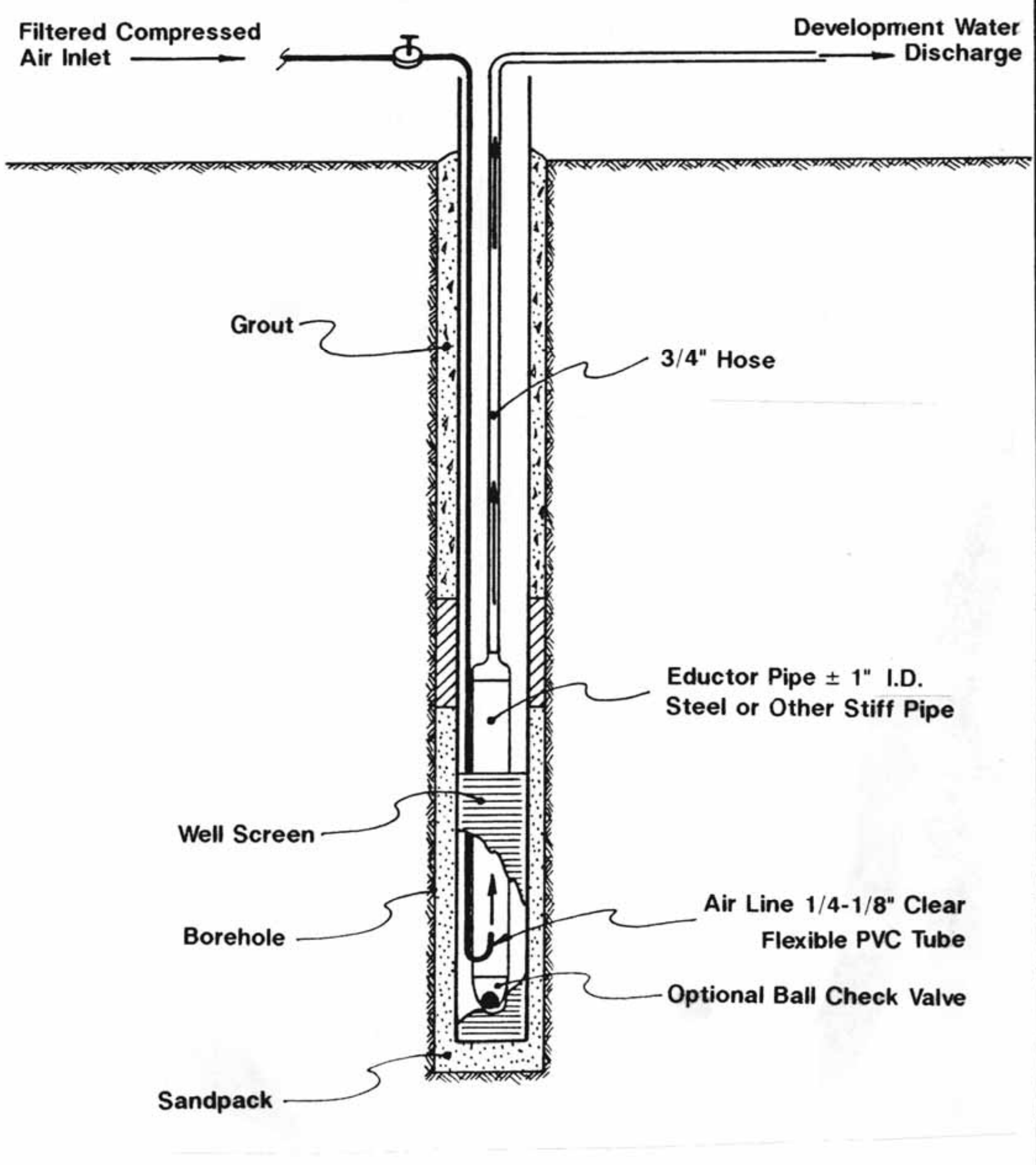

Figure 4.5-3

Source: ABB-ES

Air-lift Development System with Check Valve.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 4.6 DECOMMISSIONING OF MONITORING WELLS

SECTION 4.6
DECOMMISSIONING OF MONITORING WELLS

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4.6 DECOMMISSIONING OF MONITORING WELLS

4.6-1 PURPOSE

Any abandoned monitoring well that is no longer in use or that is unfit for its intended purposes should be decommissioned. Plugging the well and surface restoration are the central features of the decommissioning process. Plugging consists of constructing a low permeability cylinder or plug within that portion of the subsurface occupied by the well and its annulus, including the uncased portion of bedrock wells as well as the cased portion. Surface restoration consists of the removal of the upper three to four feet of the well and backfilling the area with an effective seal. An abandoned monitoring well has been defined for the purpose of these Standard References (SRs) as "a well whose use has been permanently discontinued; as used in these References it includes a monitoring well, piezometer, or observation well that is no longer suitable for use either for water-level measurements or water quality sampling."

Proper plugging of such wells will:

- o Eliminate physical hazards
- o Prevent ground water contamination
- o Conserve the yield and hydrostatic head of confined aquifers
- o Prevent the intermingling of potable and non-potable ground water, and
- o Prevent the migration of contamination through a confining layer separating aquifers.

It should be noted that the objective in Massachusetts differs markedly from the goals established by the American Water Works Association and the statutes, regulations, or guidelines of most other states. Many documents contain the following language: "The basic concept of proper sealing of abandoned wells is restoration, as far as feasible, of the controlling hydrogeological conditions that existed before the well was drilled and constructed. If this restoration can be accomplished, all the objectives of plugging wells will be adequately fulfilled." To accomplish this goal some states have suggested the placement of sand and gravel opposite the more permeable subsurface zones and clay opposite less permeable zones. While that goal is an admirable one, it is also one which, in DEP's opinion, is unattainable in practice. In order to meet the objectives of proper plugging as stated above, DEP has tried to develop a simple, workable approach that will solve the existing and potential problems from unsafe abandoned wells.

Some examples of the types of unsafe wells that may cause problems include:

- Buried uncapped wells: contaminants may enter the well through the buried top of the casing, travel down the well casing, and enter the aquifer through the well screen and wall of the annulus;

- Wells with cracked or corroded casing: surface water may enter the well;

- Improperly constructed wells: an unsealed or improperly sealed annular space around the outside of a well casing or between an inner and outer casing may serve as a channel for surface water to migrate into an aquifer and/or ground water may be transferred from one aquifer to another;

- Open hole wells in bedrock: may serve to interconnect aquifers in different formations;

- Unplugged abandoned flowing artesian wells: this can result in a loss of water, reduction of regional artesian head and localized surface flooding; and

- Uncovered and unplugged abandoned wells with large inside diameter: these may represent a physical hazard to human beings and animals, as well as a disposal receptacle for contaminants, waste, and debris.

4.6-2 PRELIMINARY WORK TO BE PERFORMED BEFORE UNDERTAKING WELL PLUGGING

4.6-2.1 Who Can Perform Proper Well Decommissioning?

One should be a registered well driller in Massachusetts or a person knowledgeable with the installation of wells in order to decommission them. There is no nationally recognized or state-approved examination or certification process for well decommissioning and plugging. However, it is obvious that a well contractor or person who is familiar with well construction and the geologic conditions of the region is preferable to a person who does not routinely perform such work. If the existing well must be "over drilled" then a registered Massachusetts well driller must perform the work. It is expected that an experienced well contractor will be familiar with the correct procedures to follow. That experience should provide substantial savings to the property owner in the long run.

The property owner should ask the well contractor about his qualifications. Some drillers or contractors specialize in rock wells; others in overburden wells. Some have worked extensively with multi-level wells at sites with contaminated ground water; others have only worked with single-level, cased water wells.

4.6-2.2 Location and Inspection

Locating the abandoned well is the first step in decommissioning. While some wells are easily located, others may be buried or otherwise concealed. It may be possible to find the location of abandoned wells through contact with past land owners, occupants, retired workers, neighbors, or well contractors. Regulatory officials and hydrogeologic reports may have useful information. The well records maintained by the United States Geological Survey (USGS), Water Supply Division, Massachusetts Section, with headquarters in Marlborough, Massachusetts, all have been assigned coordinates of latitude and longitude. For well locations, historic documents may be used, such as aerial photo and assessing maps, insurance company maps or photographs. Metal detectors may be of value in locating buried metal casings.

Obtaining accurate information on the well's original construction and present condition is the next step in decommissioning. This information is best obtained from monitoring well drilling records. Recent well records may be obtained from local Boards of Health, the Water Resources Division of the Department of Environmental Management (DEM), USGS Water Resources Division, or DEP.

Next a site inspection is necessary to ascertain the condition of the well and to note if the well is accessible, located in a pit or buried, if a dedicated pump is in place, or if the well is currently operating. The inspection should also note if the well has been damaged or obstructed. A downhole TV camera survey can sometimes provide valuable information as it can verify the current well depth, condition, construction, and the presence or absence of well casing in rock wells.

4.6-2.3 Clearing the Well

Decommissioning a well starts with removal of any obstructions, such as drop pipes, check valves and pumps, and clearing any obstacles or debris that may have entered the well.

When the well is obstructed by pumps or other equipment have been dropped down the well, the debris must be removed or "fished" out before the well can be sealed. A variety of fishing tools are used to remove obstructions. Threaded taps on the end of a drill rod may be run into the hole in an attempt to screw into the top of a pump or drop pipe. Another type of equipment used is an "over shot" (a casing with inner teeth that is run over the obstacle to be removed). Corkscrews and spears also have been used to hook the obstacle for removal.

In some instances the driller may chop or grind up the obstacles in an attempt to clear the well. Debris or other materials such as rock, sand, clay, stones, and wood is usually drilled out or washed out of the hole. This technique appears to be suitable for destroying multi-level wells installed within a single borehole.

4.6-2.4 Casing Removal or Destruction

Assuming the original well did not have an adequate seal in the annular space outside the well casing, in most cases the original well casing should be destroyed in place or pulled out of the ground.

However, if the As-Built Notes and Records indicate that the annular space contains an adequate seal, this information should enable the well contractor to design a simpler and less costly decommissioning procedure. The procedure should not require destruction or removal of the entire well casing, but would require adequate perforation of any well screen to allow the grout to penetrate the filter pack. Insert neat cement grout (or its equivalent) into the uncased portion of a bedrock well or into the filter pack around the well screen and fill the riser pipe with the same grout material. Figures 4.6-1 through 4.6-3 show the zones to be plugged through the well riser for three types of well installation where the annular space contains an adequate seal. Terminate the well casing at a minimum of 3 to 4 feet below the land surface or at the water table, which ever is encountered first. Finally, finish off the well at the land surface in a manner as described in Section 4.6-4. Figures 4.6-1 through 4.6-3 also show the zones to be prepared for a new surface finish. This procedure is appropriate for monitoring wells installed under all types of hydrogeologic conditions.

In instances where a well has penetrated a confining layer separating aquifers and there is no evidence that the annular space around the casing was adequately sealed during installation, the most conservative approach is to destroy or remove the casing by over drilling. Simply pulling the casing in this situation may result in the collapse of the formation before an adequate seal can be placed across the confining layer. The easiest way to over drill and keep the cutting bit in line with the hole (rather than straying off the hole) would be to spin casing over and around the existing observation well. The observation well will help hold the casing in line with the borehole as opposed to roller-bitting operations where an in-place casing will tend to deflect the cutting bit. Augers would probably also work in lieu of spinning casing, but spinning casing would probably be better as it is less likely to damage the observation well and, therefore, continue down the hole rather than veering off.

If, however, vertical contaminant migration across aquifers is not a concern, such as a shallow (15-30 feet) water table well in glacial sands and gravels, a choice may be made to either over drill the well, pull the well casing out of the ground or to plug the well in place. In this case, the presence or absence of annular seal is not a factor. If attempts are made to pull the casing out of the ground and the hole collapses, care must be taken to compact the materials in the hole to avoid future subsidence at the surface. Regardless of which method is chosen, the most important consideration is to seal the well from possible surface infiltration. This is accomplished by plugging the well/boring (Section 4.6-3) and terminating the well 3 to 4 feet below grade then backfilling with concrete or other appropriate seal (Section 4.6-4).

If asbestos well casing is encountered or suspected, plugging the well is the only choice. No attempt should be made to destroy or remove this material from the ground as the risk of creating a friable asbestos problem outweighs the potential negative impact from the well.

4.6-3 PLUGGING THE WELL

Neat cement (or its equivalent) should be inserted into the open portion of the well bore, whether the opening is in bedrock or overburden. As noted above, special care must be exercised if the well penetrates a confined aquifer. The low permeability layer that creates the confined aquifer must be sealed so that there is no chance of leakage between aquifers. If the hydrostatic head is large, this may present an extreme challenge to the well contractors.

4.6-3.1 Grouting Material

There are a large number of grouts available that can be used to plug abandoned wells. Each grout has certain special characteristics and distinctive properties. Therefore, one grout may be especially suited for doing a particular job. The selection of the most appropriate material or combination of materials is dependant on the construction of the well, the nature of the formation penetrated, the material and equipment available, the location of the well with respect to sources of contamination, and the cost of doing the work.

At the present time, a neat cement grout possesses most of the advantages that DEP looks for in a plug for abandoned wells where the grout will be inserted through the well riser. It may be used as grout for abandoned wells installed in all geologic formations. Neat cement is superior for sealing small openings, for penetrating any annular space outside of casings, and for filling voids in the surrounding formation. When applied under pressure, it is strongly favored for sealing wells under artesian pressure or those encountering more than one aquifer. Neat cement is also superior to other grouts as it avoids the danger of separation.

The use of bentonite pellets to plug the saturated portions of a well with a neat cement plug above is an acceptable but, less satisfactory method. The use of bentonite pellets is recommended solely for plugging shallow (15-30 feet) water table wells in highly permeable aquifers where there is no threat of vertical migration of contamination and where bridging is less likely. Care must be taken to compact the bentonite to avoid bridging of the pellets in the casing. See Section 4.2 Specifications for Wells, Screen, Filters, and Seals, for a more thorough treatment of this subject.

If the original well was not properly sealed or if there is not sufficient information available to determine whether a well was properly sealed, the most appropriate grout for such purposes appears to be a bentonite/cement grout, such as is recommended in Section 3.9 Plugging Boreholes.

4.6-3.2 Grout Placement

After clearing of the well bore, the well is ready for sealing. Grout slurries must be placed from the bottom to the top and not from the top to the bottom. In other words, slurries cannot be poured from the land surface into the borehole, annular space, or well to be sealed. When grout is placed at the bottom of the space to be grouted and finally appears at the surface or top, the integrity of the plug is assured. Methods involving pouring grout from the surface into the annular space are not reliable because bridging may occur and the depth of grout descent cannot be easily verified. However, pouring grout through a tremie tube is sometimes a satisfactory alternative to pumping through a tremie tube. An improperly sealed well may be as much a threat to ground water quality as an unsealed well.

The well contractor should calculate the volume of slurry that will be needed as described below in Section 4.6-3.3. He should have enough mixed slurry ready for placement so that it will not be necessary to stop the grouting process in order to prepare more slurry. Due to borehole irregularities, it is advisable to have on hand 25 to 50% more slurry than the calculated volume.

Grouting methods are discussed in detail in Section 4.3, Installation of Monitoring Wells. The grout pipe (or tremie pipe) method, either with or without a grout pump, appears to be a method of grout placement that will achieve all the objectives of the well plugging program.

A vigorous preventative maintenance program for mixing and pumping equipment, compressors, hoses and fittings, is essential. This includes adequate cleanup of equipment after each grout job. Failure of equipment in the field can result in: waste of grouting material, lost labor and equipment costs, property damage, contamination of the grout, and/or an unsuccessful or incomplete grout job.

4.6-3.3 Calculations and Measurements

To assure that a well is properly plugged and that there has been no bridging of the material, verification calculations and measurements are made by the well contractor to determine whether the volume of material placed in the well equals or exceeds the volume of the casing or the hole that has been plugged and/or filled. Some useful formulas for calculating well volumes are shown below:

- Gallons per 100 feet = 4.08 x (Inside Hole or Casing Diameter)^2
- Cubic feet of grout per 100 feet = 0.55 x (Inside Hole or Casing Diameter)^2
- 7.48 gallons = 1 cubic foot
- 202.0 gallons = 1 cubic yard

4.6-4 FINAL SURFACE FINISH

The contractor should return to the well no sooner than 24 hours after sealing to allow time for settlement. A proper surface seal is the final step in decommissioning a well. Where a concrete surface seal is appropriate, the remaining 3 to 4 feet at the top of the well should be filled with concrete. Form the top to create a concrete slab at least six inches thick above grade, and with a diameter at least two feet greater than the borehole wall. This procedure is more fully described in Section 4.3 Installation of Wells.

Where a concrete surface seal is not compatible with the existing land-uses (i.e., agriculture, shopping malls, residential areas, etc.) the borehole or well riser should be terminated with a minimum 1-foot thick concrete plug. The remaining 3 to 4 foot portion of the borehole should be filled to grade with materials compatible with the abutting land surface and properly compacted to minimize subsidence.

4.6-5 RECORD OF DECOMMISSIONING

Complete, accurate records of the entire decommissioning procedure should be maintained by the property owner and well contractor. The following items are especially noteworthy:

- Depth sealed The depth of all plugging materials should be recorded.

- Quantity of sealing material used The quantity of sealing material used should be recorded. Measurements of static levels and depths should be recorded.

- Changes recorded Any changes in the well made during the plugging, such as perforating casing, should be recorded in detail.

Examples of Abandoned Well Reports required by the states of Minnesota and Iowa are included as Figures 4.6-4 and 4.6-5.

4.6-6 PROHIBITIONS

The use of explosives in well-plugging operations is strictly prohibited.

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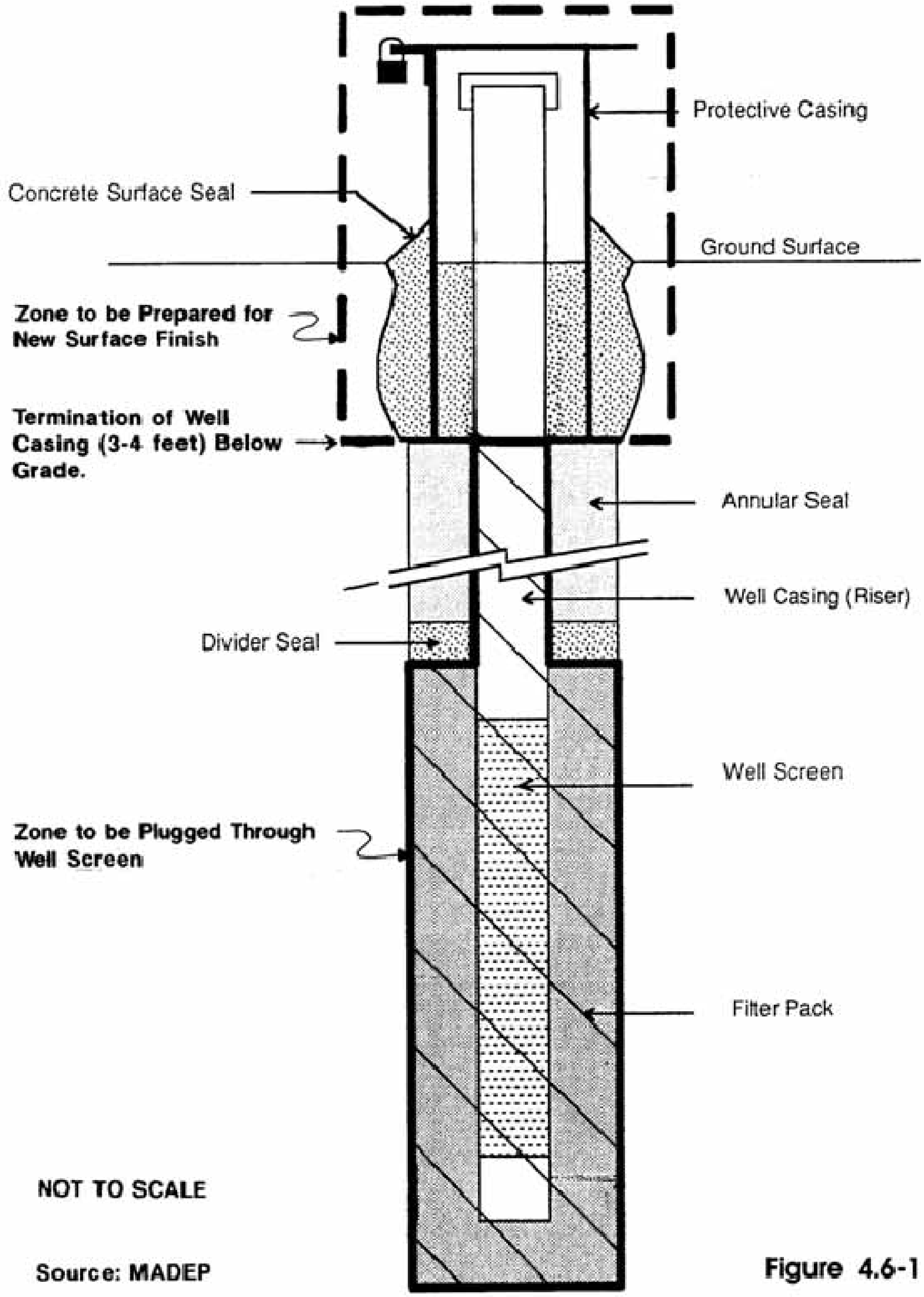


Figure 4.6-1

Diagram of an Abandoned Overburden Well.

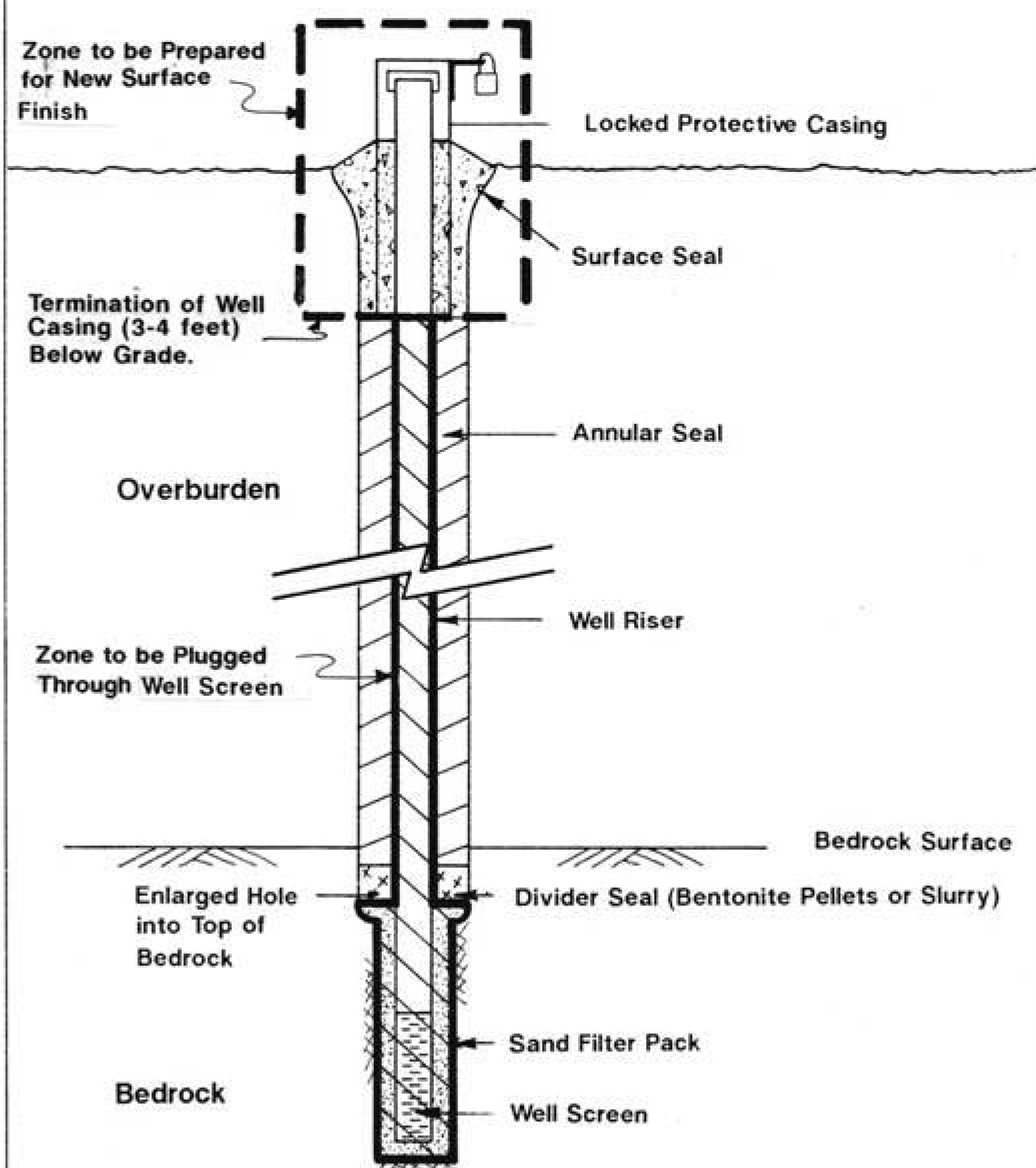


Figure 4.6-2

Diagram of an Abandoned Bedrock Well with Screen.

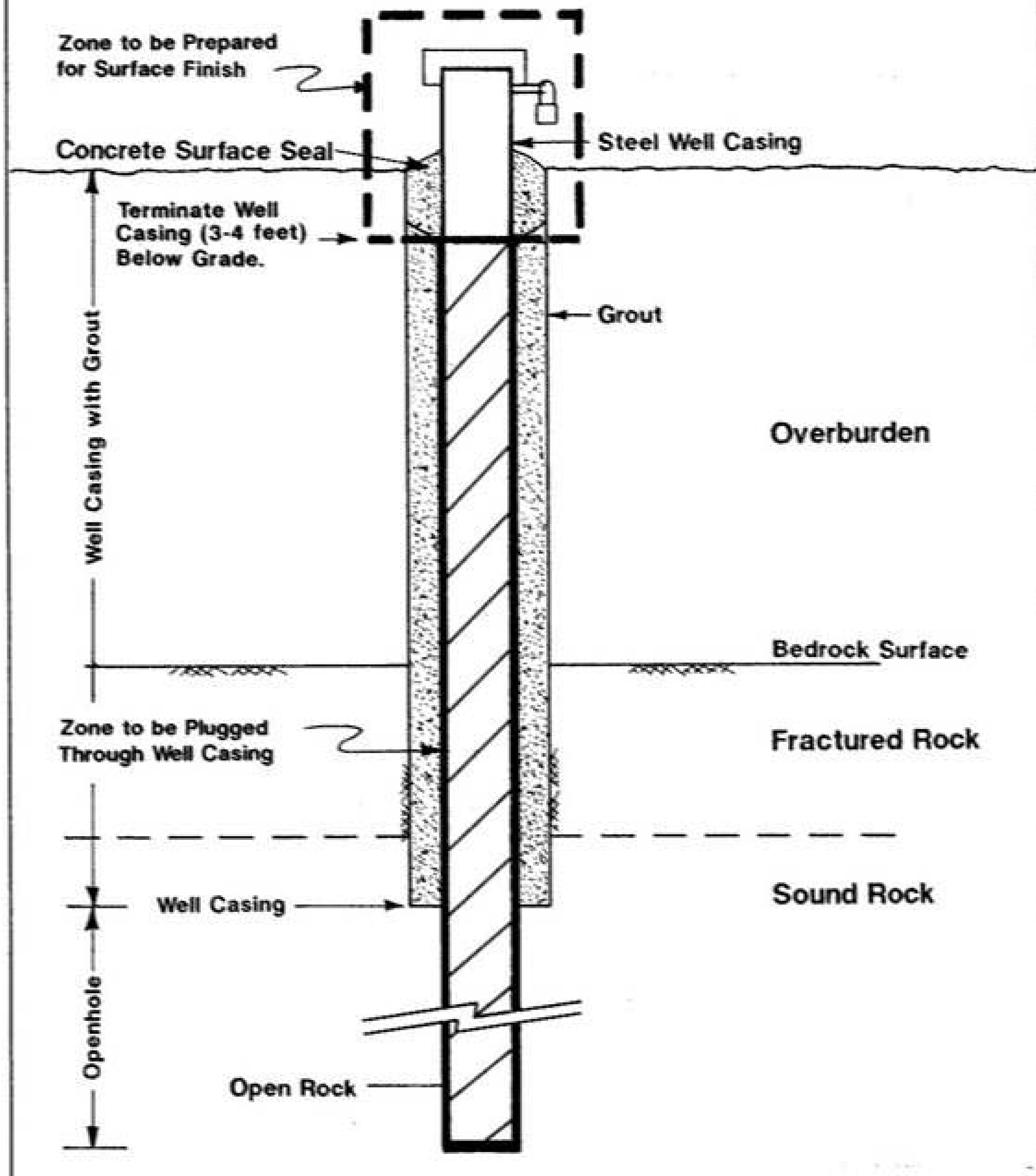


Figure 4.6-3

Diagram of an Abandoned Bedrock Well-Open Hole.

WATER WELL RECORD

MINNESOTA UNIQUE WELL NO.

ABANDONED

1. LOCATION OF WELL
County Name: Anoka
Township Name: OakTree | Township Number: 120 | Range Number: 22 | Section No.: 16 | Fraction: NW SE SE
100' East of Co. Rd 9, 200' South of Co Rd 2

Addition Name: Red Oaks
Block Number: 2
Lot Number: 1

Co Rd 2
• well
Co Rd 9

2. PROPERTY OWNER'S NAME
John Jones
Address: RR1 Box 23, Gillman, Mn 55297

4. WELL DEPTH: 126'
5. Date of Completion: drilled 1948

6. DRILLING METHOD: Cable tool

7. DRILLING FLUID

8. USE: Domestic

9. CASING: Black, Threaded. Height: 1 ft. above surface
4 in. to 122 ft.

3. FORMATION LOG

FORMATION LOG	COLOR	HARDNESS OF FORMATION	FROM	TO
*Sand	brown	soft	0	10
Clay	green	med	10	50
Clay and Sand	grey	med	50	98
Clay	blue	med	98	115
Sand	brown	med	115	126

* formation log estimated from well nearby (#101057)

10. SCREEN
Type: Brass mesh | Dia.: 4 inch
Slot/Gauze: 15 | Length: 4 feet
Set between 122 ft. and 126 ft.

11. STATIC WATER LEVEL: 52 ft. below land surface. Date Measured: 1/7/87

12. PUMPING LEVEL

13. WELL HEAD COMPLETION: At least 12" above grade

14. WELL GROUTED
Neat Cement. Grout material: Cement from 2 to 126 ft. 1 1/4 yds

15. NEAREST SOURCES OF POSSIBLE CONTAMINATION

16. PUMP
Date installed: Removed 1/7/87
Manufacturer's name: Doaks PUMP Company
Model number: B-12 HP 1/2 Volts 110
Length of drop pipe: 72 ft.
Type: Submersible

17. EXISTING WELLS
Unused well on property? No
Abandoned: Permanently

18. REMARKS, ELEVATION, SOURCE OF DATA, etc.
pump removed from well. 1 1/4 yds neat Cement installed thru tremie pipe. Casing cut off 2 feet below grade. Top 2' filled with native soil.

19. WATER WELL CONTRACTOR'S CERTIFICATION
Gopher State Well Co. 74999
Address: Box 382, Rt 1 Gillman, Mn
Signed: Henry Ramsey 1/7/87
Ralph Sibley 1/7/87

WORK COPY

F-10

Figure 4.6-4

Examples of Minnesota Abandoned Well Report.

INSTRUCTIONS

Page 1 of 2

Submit one completed copy of this form for each abandoned well that is plugged to the Department of Natural Resources, Wallace Building, 900 E. Grand Ave., Des Moines, Iowa 50319-0034 within thirty (30) days of completion of plugging operations.

Provide all of the information requested for Items 1 through 6 so far as it is known or can be obtained. If the date of construction or date of abandonment in Item 6 cannot be determined, provide the best estimate possible, such as "more than 20 years ago" or "prior to 1950."

Certification of plugging by the owner of the abandoned well in Item 7 is required for the plugging of all abandoned water wells.

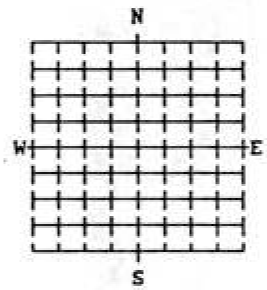
Certification of plugging by a registered well driller in Item 8 is required for all wells except large diameter (18" diameter or more) wells 100' or less in depth which are plugged by the well owner. If a registered well driller plugs this type of well, certification by the well driller is required.

1. Property Owner Name ______________________________

2. Property Owner Address ______________________________
Number and Street or RR

____
City

____
State Zip Code



LOCATE ABANDONED WELL ON THIS SECTION PLAT- 640 ACRES

3. Address of property on which abandoned well is located (if different from above)

____
Number and Street or RR

____
City Zip Code

4. Legal description of property on which abandoned well is located:

Location ____1/4 ____1/4 ____1/4, Sec.____ T.____N., ____R. ____E.W.; ________County

5. Type of Well (check one)

[] Large diameter (18" or more) well 100 feet or less in depth
[] Well less than 18" diameter or greater than 100 feet in depth
[] Sandpoint well
[] Bedrock well in a single confined aquifer
[] Bedrock well in a single unconfined aquifer
[] Bedrock well in multiple aquifers
[] Well of unknown type

Figure 4.6-5

Examples of Iowa Abandoned Water Well Plugging Record.

6. Detailed Information:

Diameter at Top of Casing ______ inches   Date Constructed ______________

Depth to Static Water Level ______ feet   Date Abandoned ______________

Total Depth ______ feet   Date Plugged ______________

Distance from nearest active well supplying potable water (check one):
[] More than 200 feet   [] Less than 200 feet

Distance from nearest point source of potential contamination (check one):
[] More than 660 feet   [] Less than 660 feet

If distance is less than 660 feet, indicate type of nearest point source of potential contamination (check one):
[] industrial waste site
[] uncontrolled hazardous waste site
[] petroleum storage area
[] hazardous waste treatment, storage or disposal area
[] agricultural chemical storage area
[] animal feedlot
[] wastewater treatment facility
[] other potential contamination source (describe) ______
____

7. Certification by owner. I hereby certify that the abandoned well described has been plugged in accordance with the requirements of Chapter 39 of the rules implementing 1987 Iowa Code Supplement section 455B.190:

____
Signature of Owner   Date

8. Certification by a registered well driller. This is required for all wells except large diameter (18" diameter or more) wells 100 feet or less in depth in Quaternary sediments.

____
Company Name

____
Address

____
City   State   Zip Code

I hereby certify that the abandoned well described was plugged under my supervision in accordance with the requirements of Chapter 39 of the rules implementing 1987 Iowa Code Supplement section 455B.190:

____
Name of Registered Well Driller   Registration No.

____
Signature   Date

Figure 4.6-5
(continued)
Examples of Iowa Abandoned Water Well Plugging Record.

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 5.1 WATER-LEVEL MEASUREMENTS

SECTION 5.1
WATER-LEVEL MEASUREMENTS

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5.1 WATER LEVEL MEASUREMENTS

5.1-1 PURPOSE

Accurate water-level measurements are essential data in any hydrogeologic investigation. Water-level measurements are taken to determine the elevation of the potentiometric surface in a monitoring well, observation well or piezometer at a particular point in time. Single-event measurements, multiple-time measurements, or continuous-time measurements may be taken. Water-level data can be used to determine the following:

- Water levels prior to water quality sampling
- Horizontal and vertical ground water gradients
- Aquifer characteristics from measurements during slug and pump tests
- Aquifer response to rainfall, barometric and tidal influences
- Aquifer response to pumping or other outside influences
- Direction of ground water flow under pumping and non-pumping conditions
- Local and regional changes in ground water levels

5.1-2 GENERAL CONSIDERATIONS

5.1-2.1 Measuring Point

A measuring point for all water-level measurements must be established and consistently maintained as a reference point on a monitoring well. The reference point should be stable and have a professionally surveyed elevation. The top of the well casing (riser) should always be used as the permanent reference point. The top of the riser is preferred over the top of protective casing because the protective casing is more susceptible to movement through settling, heaving, or displacement by impact. The reference points for both the top of riser and protective casing should be indicated with a permanent mark or notch to ensure consistent measurements. Reference points must be related to Mean Sea Level (see Section 5.5) to ensure correlation between sites.

In addition to measuring the depth to water from the top of the well riser, it is recommended that one measure the difference between the top of riser and top of the protective casing. If changes are noted with time, it is an indication that one of the reference points has moved. If there has been considerable activity (such as construction or filling) or a change is detected in the distance between the riser and protective casing reference marks, a re-survey is the only sure way of knowing that the elevations are still accurate.

5.1-2.2 Records

Manual water-level measurements should be recorded on a water-level data sheet similar to that shown on Figure 5.1-1. The unique well number, date, time, and depth to water should be recorded for each measurement. Measurements should be recorded in feet and tenths and hundredths of a foot, not inches and fractions.

The form should be drafted so that there is room for both permanent and temporary data. Permanent data include such items as unique well identification number, geographical coordinates, site address, location of measuring point, surveyed elevation of the measuring point, depth to the bottom of the well, type of well screen, length of screened interval, presence or absence of contamination, inside diameter of the well screen and riser, and hydraulic conductivity of the formation opposite the well screen. Temporary data include observations about the condition of the well, such as, volatile organic analyzer (VOA) readings, the measurement of the depth of the water level in the well, the elevation of the water level (MSL), the type of measuring device used, the data and time the readings were taken, and the name of the person taking the measurements. In addition, recording the difference in elevation between the top of riser and protective casing is recommended to verify that the reference marks are stable.

5.1-3 INSTRUMENTS

5.1-3.1 Weighted Tape (Plunker)

A plunker usually consists of a small weighted metal cylinder with a concave undersurface. When this concave surface hits the water, it produces a "plopping" sound. By lowering the plunker in the well with a gentle up-and-down motion, the water surface can be determined. Usually the plunker is attached to a 100-foot steel or fiberglass measuring tape. A direct reading of the depth to water can be obtained if the tape has been shortened a distance equal to the length of the plunker.

If a permanent adjustment has not been made to the tape, it is not possible to obtain a direct measurement of the water level. With an unadjusted tape a compensating calculation must be made each time, to add the distance between the tape and the end of the plunker to the depth measured directly from the tape. The accuracy of this method is approximately 0.05-0.1 foot. If a steel tape is used, the weight of the plunker should be adjusted to offset the weight of a long tape.

Advantages

- Simple to operate.
- Simple and inexpensive to construct; can be dedicated to a well.
- Generally unaffected by most ground water contaminants.
- With tape modification it provides a direct reading of depth to water.

Disadvantages

- o Not suitable for deep measurements (i.e., over 100 feet).
- o Not suitable when ambient noise levels are high (e.g., pumps or drill rigs operating nearby).
- o Not suitable if the well contains dampening substances (e.g., high percentage of sediments or viscous liquids).
- o Unadjusted tape is a potential source of error.
- o Very difficult to hear "plop" when the top of water is in the screened section.
- o Not suitable for determining thickness of floating fluid.
- o Fiberglass tapes may stretch, providing inconsistent readings.
- o Unless treaded with teflon the fiberglass tape may stick to casing.

5.1-3.2 Chalked Tape

This method is not recommended in wells that are also being used for water quality sampling due to the fact that the chalk may introduce impurities into the well.

A steel or fiberglass tape coated with chalk with a small diameter weight attached to the end can be used to obtain water-level measurements in a well. The lower 3 to 4 feet of the tape is rubbed with chalk, and the tape is lowered into the well until the lower part is submerged and an even foot mark is at the measuring point on the well. The length of the wetted section of the chalked tape is subtracted from the total tape measurement to obtain the depth to water. The accuracy of the chalked tape device is on the order of 0.05 foot.

Chemically sensitive chalks or coatings can be used to determine the presence and thickness of fluids other than water, such as gasoline. These substances can be spread on a coated steel tape and the depth and thickness of the substances can be determined from the color change on the tape.

Advantages

- o Simple, easy to operate.
- o Not subject to mechanical or electrical failure.

Disadvantages

- o Dripping water and condensation can result in erroneous readings.
- o Chalk may introduce unacceptable impurities into the water.
- o Requires subtracting the wetted length for total measurement - not a direct reading method.

5.1-3.3 Electrical Tapes

Electrical water-level tapes are based on the principle that once the probe (consisting of two unconnected wires located on the end of the tape) is immersed, an electrical circuit is completed and a buzzer and/or a light is activated. Electrical water-level tapes are usually marked in one- to five-foot intervals. Therefore, the intermediate distance must be measured with a ruler to determine the actual depth to water. A few instruments recently introduced and commercially available are fully marked, allowing for a direct measurement in feet or meters. Accuracy of this method is approximately 0.05 feet.

Advantages

- o Small diameter (¼- to ½-inch) cable and probe is capable of measurements in small diameter piezometers.
- o Relatively simple to operate.
- o Multiple readings during slug and pump tests are possible without removing tape from the well.
- o The individual tape length is the only depth limitation.
- o Background noise is not a problem.

Disadvantages

- o Dripping water or condensation on the sides of the well riser can result in erroneous readings.
- o The tape may become kinked and will not hang straight in a well, producing inaccurate readings.
- o If the tape requires a manual measurement between markings, it is subject to error; it may not be suitable where fast measurements are required.
- o The instrument is subject to electrical malfunction (e.g., dead batteries or cable breaks); also, one-foot markings may shift, resulting in inaccurate readings.
- o Not suitable for wells with PCBs or other di-electric fluids.

5.1-3.4 Transducer

A pressure-sensitive transducer can be used to measure water levels in a well. Transducers displace water when they are lowered into a well. One must be sure to allow adequate time for the water level to equilibrate. The pressure transducer produces an electrical signal (voltage or amps) proportional to the height of the water column above the transducer. The pressure is recorded in pounds per square inch (psi) which can then be converted to feet of water. A display meter, data logger, recorder, or similar instrument must be used to interpret the transducer signal. The output may be displayed on a meter, recorded on a chart, or fed directly into computer memory for later data reduction. Transducers are particularly suitable for slug tests or pump tests where frequent, rapid readings or long-term measurements are desirable. The accuracy of the water-level measurements depends on the type of data logging instrument used, and the psi range of the transducer (e.g., 10, 25, or 50 psi). Accuracy, usually 0.1 percent of full scales, ranges from 0.01 to 0.2 feet for most common transducer ranges. The data generated is referenced to the elevation (i.e., depth below a reference mark) of the transducer. The position (i.e., depth or elevation of the transducer) must be calculated for each well or testing event.

Advantages

- Continuous and rapid readings possible.
- Can operate remotely for long periods of time.
- Can provide for direct access to the data on a computer.
- Length of the individual transducer cable and the transducer pressure range is the only depth limitation.

Disadvantages

- Equipment is expensive.
- Operation is moderately complex and sophisticated.
- Subject to electronic failure or data transmission loss.
- Some instruments are not weatherproof and require special protection from inclement weather.
- Subject to reduced accuracy if not checked regularly and calibrated properly.
- May not be resistant to certain chemicals.
- Voltage must be held constant.
- Will give inaccurate readings if not vented to compensate for barometric pressure changes.

- Use over long periods must account for changes in atmospheric pressure.

- Probe constants are determined for water, which has a specific gravity of 1.0. False readings may be obtained or compensating adjustments must be made for substances with a specific gravity less than or greater than 1.

- If a data logger is dedicated to a particular well, it may be conspicuous and encourage vandalism.

5.1-3.5 Acoustic Well Probe

Acoustic well probes operate on the same theory as sonar or similar sonic depth-finding devices. Acoustic well probes use ultrasonic sensors or transducers to transmit a signal and record the amount of time it takes for the reflected signal to return to the sensor. This information can then be translated into depth to water. Accuracy reportedly ranges from 0.5 to 1.0 feet for different models commercially available. This level of accuracy may be unacceptable for many projects.

Advantages

- Probes do not contact liquid; therefore, they are particularly suitable for highly contaminated environments, or highly viscous contaminants.

- Eliminates the potential for cross-contamination between wells.

Disadvantages

- Equipment is expensive, relatively new and untested.
- Operation is moderately complex and sophisticated.
- Accuracy may be influenced by temperature changes.
- Accuracy may not be adequate for many applications.

5.1-3.6 Continuous Water-level Chart Recorder

A continuous chart recorder can be used to record water levels over periods of time ranging from 4 hours to 32 days. Typically, the recorder consists of a float mechanism attached to a drum chart recorder. The relative level of the float is recorded on the chart for the time period specified. The final chart is a plot of relative water levels versus time.

Recently, quartz clocks have replaced the original key-wound clocks in these recorders, increasing the reliability of the instrument. Continuous chart recorders were originally designed for surface water monitoring, such as stream gauging, but they have been adapted to ground water monitoring by the use of small-diameter floats. More sophisticated systems are capable of translating the data into digital information and transmitting the data to a distant receptor.

Advantages

- o Provides almost continuous water-level record.
- o Accurate from 0.01 to 0.05 feet.
- o Relatively simple to operate.
- o Recognized as a well-proven method used by USGS.

Disadvantages

- o Subject to mechanical problems, particularly in cold weather.
- o Requires box or compartment attached to well.
- o Floats and cable move with water-level fluctuations, and may become stuck or lodged in well.
- o It is subject to extraneous interference from vibrations caused by trains, earth tides, etc.
- o Large water-level fluctuations may be difficult to interpret, particularly near pumping wells due to overlapping impacts on water levels.
- o The recorder is conspicuous, and may be vandalized. It needs a protective cover.

5.1-3.7 Interface Probes

Interface probes consist of a small probe attached to the end of a coated tape that includes an optical liquid sensor and an electrical conductivity probe to differentiate between water and non-polar liquids (i.e., hydrocarbons). The probe transmits a signal up the tape to the reel, where an audible alarm emits a tone: a continuous tone for hydrocarbons and an oscillating tone for water. A direct reading of the depth of free product and of the water level can be made from the tape. The interface probe can also be used to measure water levels where floating hydrocarbons do not occur. The accuracy of this method is approximately 0.05 feet. It is advisable to cross-check the measured hydrocarbon thickness by retrieving a sample of the product and observing its thickness in a clear bailer.

Advantages

- o Permits measurement of the depth and thickness of separate phase liquids, as well as water levels.
- o Useful for water-level measurements alone.
- o Direct reading possible.

Disadvantages

- o Battery-operated and subject to possible electrical malfunctions.
- o If the signal or light is not on the reel, but on the probe, it may be difficult to hear the tone or see the light.
- o Probe diameter is 1¼ inches; may be too large for some piezometers; could become lodged in riser.
- o Probe may be affected by decontamination solutions.
- o For high viscosity fluids (i.e., No. 6 fuel oil), accurate readings may be difficult to obtain.
- o Difficult to decontaminate.

5.1-4 METHODOLOGY FOR MEASURING WATER LEVELS

Water level measurements are so important in interpreting site hydrogeology that a clear, concise, well-ordered methodology is imperative. The following checklist is offered to ensure consistant and accurate data.

1. Prior to going into the field, check the measuring equipment to be sure that it is working properly and that it is in good repair. Also, prior to undertaking field work, the equipment should be decontaminated. Carry extra equipment and batteries to eliminate lost time in the event of equipment loss or malfunction.

2. Prior to entering the field, fill out the field forms with the permanent well data, such as well number, depth to the bottom of the well, and elevation of the permanent measuring point. Bring a current site map showing the location and identification numbers of all wells.

   When collecting measurements, it is useful to bring along previous water-level data. Comparison of the current measurement to previous measurements can help identify anomalous readings or misread well numbers.

3. Unlock the padlock in the hasp. Remove the protective cap from the well. Check that the I.D. number on the cap is the same as the one entered on the permanent record. Record any unusual sounds, odors, staining, damage, or other observations in the "Remarks" column. Be alert for evidence of vandalism or tampering.

- o Well risers should be vented during installation by drilling a small hole into the casing below the depth of the seated cap (see Section 4.3). This will permit air and gas to escape during water level fluctuations. If a popping or sucking sound is heard when the cap is removed, the well is probably not vented properly. If the well is not adequately vented, the water level may take a while to stabilize once the cap is removed, especially in low permeability materials.

- o If the well has been completed in contaminated ground water, appropriate health and safety protection and procedures must be utilized (see Section 2.3). Generally, an OVA is used to monitor for volatile organics immediately upon opening the well.

4. First check for the measuring point. Holding the instrument at this point obtain a water-level reading with the measuring device. Record the actual reading obtained from the instrument - do not correct or convert data in your head. Repeat the measurement again to confirm the reading. Under ideal conditions the measurements would be taken using two different kinds of instruments. The reported depth would be the average of these two readings. Remember to record the time of the measurement.

5. Measure and record the difference in elevation between the reference marks on the top of well riser and protective casing.

6. Measure and record the depth to the bottom of the well.

7. Remove the instrument from the well. If the well is located at a site where contamination is suspected or known to be present, the measuring instrument must be completely decontaminated before taking another measurement in another well (see Section 6.5).

8. Replace cap and secure the well.

9. Once the measurements are complete, translate the water level depth readings into elevations (NGVD).

5.1-5 PROBLEMS AND POSSIBLE SOLUTIONS

5.1-5.1 Cross-contamination

Where contaminated groundwater exists, care must be taken to avoid cross-contamination of wells caused by contaminated water-level measuring instruments. Adequate decontamination procedures or dedicated instruments should be used to avoid this problem. It is advisable to start with the cleanest wells and work progressively to the more contaminated wells. Use historical data to determine this order.

5.1-5.2 Water/Floating Fluids

If immiscible fluids with a specific gravity that is less than 1 are encountered in a monitoring well, special procedures may be required to obtain a free product/water-level measurement. Instruments, such as an interface probe, are available that will measure the water/product levels. In the case of highly contaminated ground water or non-aqueous phase liquids, special dedicated instruments may be required for water level measurements. Where immiscible, floating fluids are encountered, measurements of both fluid levels should be recorded during each measuring event. Without correction water level contour maps prepared on the basis of a 2-phase liquid surface will always contain some unavoidable errors.

5.1-5.3 Flowing Artesian Wells

In order to obtain accurate measurements in flowing artesian wells, the water level must be stabilized. This is generally accomplished by adding an additional section of riser pipe onto the well to stabilize the flow so as to permit the measurement of a water surface below the top of the added riser or by using a pressure gauge. If additional riser pipe is added, a new measuring point for the well must be established, documented, and reported. Water pressure gauges can be adapted to fit over the top of the riser and measure the artesian pressure at the wellhead. The elevation or height above ground can be calculated from the pounds per square inch (psi) reading of the instrument. If flowing artesian conditions are anticipated, wells can be constructed to allow for the necessary riser additions or the use of a pressure gauge. If artesian conditions are anticipated, the surveyor conducting the original survey should be asked to establish a permanent reference datum that can be used as a reference point for future changes.

Measurement of water levels in flowing artesian wells may be impossible to obtain if the water column freezes above the ground.

5.1-5.4 Cyclic External Factors Affecting Water Levels

Water levels may be influenced by any combination of pumping, barometric and tidal influences. In general, tidal and pumping influences produce the most extreme deviations from undisturbed conditions. If tidal influences are a possibility at a site, ideally it is advisable to monitor the water levels in selected wells for a full 28-day tidal cycle to determine the significance of this factor. This can be roughly approximated by taking just two measurements: one at high tide and one at low tide in the middle of a 28-day tidal cycle. Nearby pumping wells can also significantly alter natural water-level elevations. If interfering pumping conditions are encountered, water levels should be measured during periods of pumping and non-pumping conditions when the water level has stabilized. A continuous water-level recorder is preferred for this type of monitoring. If anomalous measurements are obtained or pumping is occurring, these factors need to be evaluated. All water level measurements should include the time that the measurement was obtained. Use of the military or 24-hour time designation will eliminate the possibility of confusing A.M. with P.M. readings.

5.1-5.5 Non-cyclic External Factors Affecting Water Levels

Trenches in which underground utilities such as water, gas, sewer, and transmission pipelines are laid, disturb the natural permeability of the soil, increasing its hydraulic conductivity. At times ground water infiltrates directly into underground vaults and pipes. Taken collectively these features may represent line sinks or sources - places where ground water will tend to discharge or recharge preferentially. If a site has a large number of monitoring wells closely spaced together, the effects of these will be readily apparent on a map of the potentiometric surface. If the density of the wells is less, the water levels may produce anomalous readings that defy interpretation.

5.1-5.6 Dropping Something into a Well

Caution should be taken to avoid dropping objects into a well. Pencils, keys, eyeglasses, and other loose objects easily drop into wells, but are not so easily retrieved. All measuring instruments should be connected to something larger than the diameter of the well riser to avoid dropping these down a well. Measuring instruments should have a diameter small enough so that they fall freely in the well. This will avoid lodging the device in the riser, thereby obstructing further measurements or sampling. All measuring tapes or cables should be in good repair, free from breaks or splits that could result in separation of a cable within a well. Fishhooks and string may sometimes successfully retrieve lost items. Extreme care must be taken when taking water-level measurements in pumping wells to prevent entanglement of the measuring instrument on downhole equipment.

ADDITIONAL REFERENCES

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WATER-LEVEL MEASUREMENTS

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Water Level Measurements

Project Number ________ Project Location ________________________ Date ____________

Measuring Instrument ________________ Field Person ______________________________

Well Number	Elevation Top of Well Riser (M. S. L.)	Distance Between Top of Well Riser and Rim of Protective Casing		Depth to Water from Top of Well Riser	Elevation Water Level (M.S.L.)	Time
		(Last)	(Today)			

Source: MADEP

Figure 5.1-1

Example of a Water-level Record Sheet.

SECTION 5.2
IN-SITU HYDRAULIC CONDUCTIVITY TESTS

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5.2 IN-SITU HYDRAULIC CONDUCTIVITY TESTS

5.2-1 PURPOSE

In-situ tests to determine hydraulic conductivity (K) should be performed in nearly all hydrogeologic investigations. Hydraulic conductivity can be determined from both field and laboratory tests. Laboratory tests, such as permeameter tests and grain-size analysis, are discussed in Section 3.8 Laboratory Tests of Soil and Rock. Packer tests and pumping tests are additional field techniques that can be used to obtain in-situ data about hydraulic conductivity. The applications and requirements of these tests are presented in Section 5.3 Pumping Tests and Section 5.4 Packer Tests. This Standard Reference (SR) provides guidelines for the measurement of in-situ hydraulic conductivity using boreholes or monitoring wells. These tests are often referred to as "slug" or "permeability" tests. This SR presents a discussion of the various applications, test procedures, and data interpretation methods that can be used.

As shown on Table 5.2-1, hydraulic conductivity values for natural soil and rock materials vary over more than 10 orders-of-magnitude. At many sites, the point-specific hydraulic conductivity varies spatially (i.e., vertically and horizontally) by several orders-of-magnitude. The need to define the variability of the hydraulic conductivity (K) will depend on the objectives of the investigation. For water-supply investigations, minor variations in hydraulic conductivity may not be important. In contaminant transport modeling, however, any variation and spatial distribution of hydraulic conductivities may be of prime importance in estimating rates and directions of contaminant movement. Knowledge of the spatial variation can be especially valuable in interpreting the depositional environment to extend prediction of the contaminant movement outside the area tested.

When comparing various techniques for measuring hydraulic conductivity, it is important to recognize the scale of the test measurement and how that relates to the objectives of the investigation. Laboratory tests can be used to measure hydraulic conductivity of cohesive undisturbed samples that range in vertical length from a couple of inches to a few feet. By comparison, pumping tests may evaluate the entire aquifer thickness, a sample on the order of tens to several hundred feet in thickness. In many cases it is advisable to perform several types of tests, at different environmental scales, in order to raise the level of confidence in data interpretation.

In-situ measurements of hydraulic conductivity have the following advantages and disadvantages as an aquifer characterization method:

Advantages

- o This method allows the estimation of in-place hydraulic conductivity.
- o The methodology eliminates the problems associated with collection of undisturbed samples and the effects of testing apparatus associated with laboratory tests.
- o Tests can be performed quickly in the field and at low cost. The drilling of observation wells and multi-day pumping tests are not required.
- o At contaminated sites, treatment of contaminated discharged water is minimized.
- o Unlike conventional pumping tests, in-situ tests allow for the estimation of the hydraulic conductivity of discrete zones within an aquifer.

Disadvantages

- o Only the hydraulic conductivity in the immediate vicinity of the well or borehole is measured; this may not be representative of the average hydraulic conductivity of the aquifer or even the tested zone.
- o Because test data analysis requires many simplifying assumptions, the hydraulic conductivity values are generally accurate only to an order-of-magnitude.
- o Unlike pumping tests, the storativity parameter (S) or specific yield (Sy) usually cannot be determined.

Measurements of hydraulic conductivity are of fundamental importance in almost all hydrogeologic investigations. Hydraulic conductivity values are used:

- o To estimate rates of ground water flow.
- o To estimate responses of aquifers to applied stresses, such as pumping.
- o To estimate the rate of movement of various chemicals in tested subsurface zones.
- o To identify zones favorable for development of ground water resources.
- o To estimate soil or rock transmissivity where pumping tests are not feasible due to extremely low permeabilities or highly contaminated ground water.
- o To construct and calibrate ground water flow models.

5.2-2 THEORY OF FLOW THROUGH SATURATED POROUS MEDIA

Hydraulic conductivity is a measure of the ease of flow of a specific fluid through a specific porous medium. Hydraulic conductivity was first described by the empirical relationship known as Darcy's Law, which states that the flow rate (Q) through a given cross-section of porous media (A) is directly proportional to the hydraulic gradient (dh/dl) and the hydraulic conductivity (K). Hydraulic conductivity is also known as the coefficient of permeability. The two-dimensional expression of Darcy's Law is:

$$Q = K\,A\,(dh/dl)$$

where,

Q = flow or discharge (volume/time)
A = cross-sectional area (length squared)
dh/dl = hydraulic gradient (length/length; dimensionless)
K = hydraulic conductivity (length/time)

Hydraulic conductivity is a function of the properties of the fluid and the properties of the porous medium. The fluid properties that influence hydraulic conductivity are the fluid density and viscosity. The influencing properties of the medium are porosity, particle size, shape, distribution, and sorting. Consequently, K will vary for the same fluids in different geologic materials and for different fluids (e.g., water and oil) in the same geologic materials.

The terms permeability and hydraulic conductivity are often used interchangeably. This can be confusing. In the strictest usage, permeability, or intrinsic permeability, is the property of the porous solid material through which a fluid is moving. Intrinsic permeability is generally expressed in units of darcys, and is represented by the letter "k" (lower-case). The relationship between hydraulic conductivity and intrinsic permeability is expressed in the following equation:

$$K = k\frac{\rho\, g}{\mu}$$

where,

K = hydraulic conductivity (length/time)
k = intrinsic permeability of the porous media (length squared)
ρ = density of fluid (mass/length)
g = acceleration of gravity (length/time)
μ = dynamic viscosity of fluid (mass/length time)

This equation becomes important when dealing with fluids having a specific gravity greater or less than 1. Typical values for hydraulic conductivity and intrinsic permeability for a wide spectrum of geologic media are presented in Table 5.2-2.

Intrinsic permeability is a property of the porous media regardless of the fluid it contains. It is defined by the equation:

$$k = C\, d^2$$

where,

- k = intrinsic permeability (length squared)
- C = a 'shape' factor (dimensionless)
- d = mean grain-size diameter or effective grain diameter (length squared)

When water is the only fluid in question, hydraulic conductivity values are often used to compare variations in the intrinsic permeability of the media. It should be kept in mind that hydraulic conductivity will vary if either the properties of the fluid or the media change. Large differences in water temperature will also affect hydraulic conductivity values. Fluids, such as creosote, that have densities different from water will also affect the hydraulic conductivity values. For additional information on hydraulic conductivity, the reader is referred to any introductory text on ground water or hydraulics, such as Freeze and Cherry (1979) or Fetter (1988).

5.2-3 IN-SITU TESTS AND TEST PROCEDURES

5.2-3.1 Test Conditions

In-situ tests to determine hydraulic conductivity can be conducted either in open boreholes as drilling proceeds or in monitoring wells after they are installed and developed. In-situ tests can be divided into two types: 1) variable-head tests and 2) constant-head tests. If monitoring wells are used for water-quality sampling, it is often preferable to perform a rising-head test to avoid the introduction of water that does not originate within the formation. Prior to testing, all monitoring wells should be developed to a point that further development does not result in a noticeable increase in water yield. Variable-head and constant-head tests can be performed in either an open borehole or a screened well.

5.2-3.1.1 Borehole Tests

Two types of borehole tests can be performed during the advancement of cased boreholes. A flush-bottom test makes use of only the bottom cross-sectional area of a borehole, while an open hole test is conducted on a section of uncased hole. A flush-bottom test is one in which casing is advanced to the bottom drilling depth; it provides an estimate of the vertical hydraulic conductivity. On the other hand an open-hole test generally provides an estimate of the horizontal hydraulic conductivity, because normally the side-wall area of an open hole is much greater than its bottom area. If open-hole tests are to be performed in poorly consolidated formations, it may be helpful to fill the casing with clean coarse sand for the desired test interval and then carefully pull back the casing to just below the top of the sand. The hydraulic conductivity of the sand must be significantly greater than the hydraulic conductivity of the formation, and not impose resistance to water movement. This technique will help to prevent collapse of the borehole walls during exposure of the test zone. Flush-joint casing should be used in boreholes where in-situ tests are planned. If field tests are planned in cased holes, care should be taken during drilling to minimize disturbance and smearing on the borehole walls. In many cases, augered holes are not suitable for open borehole tests due to the unavoidable smearing and disturbance of the soil and borehole walls. Flush-bottom tests run inside an open-end auger flight also may give erroneous data due to the excessive water leakage through auger flight joints.

5.2-3.1.2 Tests in Monitoring Wells

The test procedures for monitoring wells are essentially the same as for boreholes, except that the test zone is pre-determined by the location of the screen and sand pack. Figure 5.2-1 shows the typical design of a monitoring well and the configurations of measurements pertinent to hydraulic conductivity tests. The total length of the test zone (L) should be determined as the total saturated length of the sand pack, including all of the screened interval. Monitoring well tests provide estimates of horizontal hydraulic conductivities.

The maximum hydraulic conductivity that can be measured in any given well may be limited by the hydraulic conductivity of the sand pack and by the open area of the screen.

5.2-3.2 Variable-head Tests

Variable-head tests are performed by causing a sudden ("instantaneous") rise or drop of the static water level in a borehole or well casing or riser. This deviation from the initial head (static water level equated to zero) is termed excess head.

5.2-3.2.1 Falling-head Test

A falling-head test is initiated by either quickly injecting water into the well or, preferably, by displacing the standing water upward with a tube-shaped slug to create an excess head. The drop in water level with time is measured as the excess head declines to zero (the static water level). For a given well construction, the rate at which the water level drops is controlled by the formation characteristics, provided that the well was properly constructed. A plot of head data (H-x) versus time data ($t-t_o$) is used to calculate the hydraulic conductivity. Figure 5.2-1 shows, schematically, a falling-head test.

Falling head tests should not be performed in wells where the screened interval straddles the water table. To measure hydraulic conductivity, the well screen must be placed entirely within the saturated portion of the aquifer. If the top of the screen is at, or close to, the present water table, rising head tests should be performed.

5.2-3.2.2 Rising-head Test

A rising-head test is quite similar to a falling-head test except that the water is suddenly displaced downward in the casing or riser pipe. In this case, the dissipation of negative excess head will be measured. The immediate water-level rise (x-H) is plotted against time after the depression is initiated ($t-t_o$), and these data are used to calculate the hydraulic conductivity. Figure 5.2-1 also illustrates a rising-head test.

5.2-3.2.3 Requisite Data

The location of the well screen or test zone with respect to the geologic materials shown on a boring log must be known. In order to calculate the hydraulic conductivity, the following information must be recorded:

H	-	static water level prior to start of test.
r	-	radius of the inside of riser pipe.
R	-	radius of the bottom of the casing or, if more appropriate, one-half the effective diameter of the borehole.
L	-	length of the zone below the casing in a open hole test, or the length of the screen and saturated filter pack for monitoring wells.
Ho	-	initial excess head at time t = 0 (to).
h	-	the amount (length) of positive or negative excess head that is created in the well or borehole.
($x, x, x...x_n$)	-	water-level head measurements at various times (t).
(t, t2, t3..tn)	-	elapsed times corresponding to the times when water-level (head) measurements are made.

These relationships and related measurements are illustrated in Figure 5.2-1.

5.2-3.2.4 General Test Methods

The following procedure presents a general method for performing a slug test. There are a number of variations to this general method developed for specific hydrogeological conditions. The variations presented in the following sections should be researched before the test is performed.

(a) Slug Injection or Withdrawal

The height of water displacement caused by slug injection or withdrawal must be accurately known in order to calculate the hydraulic conductivity based on the head difference at different time intervals. The preferred technique of creating water displacement upward for a falling-head test is to suddenly lower a weighted cylindrical solid beneath the static water level. By knowing the volume of the cylinder, the height of rise in water level (H_o) can be calculated for any diameter well. The technique of quickly pouring water in the well ("slugging"), commonly used in the past, gives significantly less accurate values of hydraulic conductivity in moderately to highly permeable media. The slug should be injected as quickly as possible. It is important to remember that a falling-head test should not be conducted when the initial static head in the well is below the top of the screened zone or the test will be affected by unsaturated conditions in the filter pack and the aquifer.

To create a downward displacement of the water column with respect to static level, either of two techniques is recommended. If water quality integrity is of concern or if the formation is believed to be highly permeable, the well can be pressurized with compressed air at the well head. At $t = 0$, the pressurized plumbing is suddenly vented and kept open. The other technique is to lower a weighted cylinder just below the static level and, upon water-level equilibration to static, remove the cylinder quickly. This procedure follows naturally after the cylinder-displacement rising-head test described above. Under certain circumstances and if the formation is not very permeable, a bailer or well pump may be satisfactorily used to remove a measurable volume of water over a period of several seconds.

(b) Equipment for Water-level Measurements

Once the excess head has been produced by either lowering or raising the water level, the altered water level will decay to its initial static level at a rate directly related to formation permeability. Measurements of the water levels at regularly timed intervals after the start of the test should be recorded. Figure 5.2-2 is an example of a field form that can be used to record data when conducting a variable-head test in a borehole.

If the formation materials are relatively homogeneous, the water level will recover at a logarithmic rate, with rapid recovery occurring during the early part of the test. In highly permeable formations, the measurement of water levels at frequent intervals is particularly critical during the early part of the test. The frequency of measurement is the same as that discussed in Section 5.3-5.3 and shown in Table 5.3-1.

Various types of equipment can be used to take water-level measurements, including "plunkers," chalked tapes, electric water-level meters, interface probes, and pressure transducers. Section 5.1 Water-level Measurements contains information on various types of water-level measuring equipment. The selection of the measuring equipment should be based on the anticipated rate of recovery. In highly permeable sands and gravels, water levels may recover almost immediately, making accurate manual measurements impossible. A pressure transducer, an instrument that can record the hydrostatic pressure of the column of water above the transducer (i.e., water levels) at an extremely rapid rate, is required for tests under these types of conditions.

(c) Duration of the Test

The length of time required to obtain sufficient test data is dependent on the volume of the slug (i.e., initial height of excess head), the hydraulic conductivity of the formation, and the configuration of the test zone. If the test zone is relatively permeable, the water level should be monitored until it returns to the initial static level.

If the test data are being collected manually, excess head versus time data should be plotted on a semi-log plot as the test proceeds. In order to calculate a valid hydraulic conductivity, a portion of these data should plot as a straight line on a semi-log plot. Once a sufficient number of readings are obtained for determining the straight-line fit, the test can be terminated. A second test (i.e., duplicate test) in each well or borehole is recommended as a check on the accuracy and reproducibility of the results.

Using the best preliminary estimate of hydraulic conductivity (K), the analytical equations discussed in this section can be used to estimate the amount of time required for an in-situ field test. If the hydraulic conductivity is quite variable at the site, the sequence of tests should proceed from the lowest permeability to the highest to allow adequate time for recovery of formations with low values of hydraulic conductivity.

5.2-3.2.5 Test Procedure for Boreholes and Monitoring Wells

The following procedures can be used for in-situ hydraulic conductivity tests conducted in either temporarily cased boreholes or in finished monitoring wells. Due to the stable borehole condition of a monitoring well, tests conducted in a temporarily cased borehole presents more potential for hole condition irregularities, and the procedure is more demanding. Steps 1 through 7 are used in borehole tests, while only Steps 3, 4, 5, and 6 are necessary when a test is run in a monitoring well.

1. Advance casing to the desired depth.

2. Carefully wash out all the material to the bottom of the casing until the wash water remains clear. If an open-hole test is desired, carefully pull back the casing to an appropriate depth. Just prior to pulling back, the casing can be filled with coarse sand to prevent collapse of the borehole walls when the casing is pulled back. The water level in the casing must be maintained at or above the static water level to prevent collapse of soil into the borehole or the movement of soil up the casing. This is particularly important during the removal of the drilling rods. Measure the depth of the hole to determine if any voids were created below the bottom of the casing. If a void is found, lower

the casing below the void and carefully repeat the drilling and washing procedure.

3. Measure the static water level from the top of the casing; confirm this reading with a second measurement five minutes later.

4. To conduct the test, fill the casing with clean water to the desired height above the static water level or lower the water level to the desired depth. Typically, excess heads of 5 to 20 feet are used. The choice of the length of the imposed head will depend on the depth to the static water level, the permeability of the formation, and the amount of time allowed for the test. The greater the excess head imposed during the test, the faster the rate at which initial recovery will occur.

5. Obtain water-level measurements at the prescribed time intervals until the water level stabilizes or adequate recovery data have been obtained.

6. Check for leakage during the test; air bubbles rising in the casing may indicate leakage around casing joints. Also, check for water flowing between the outside of the casing and the ground surface, indicating a leaky seal between the casing and borehole walls.

7. After the test has been completed, measure the depth of the borehole to determine if any caving has occurred during the test. If caving has occurred, the test-interval length (L) existing at the end of the test should be used in the calculations.

5.2-3.3 Constant-Head Test

In a constant-head permeability test, water is added to the well or borehole at a rate sufficient to keep a constant water level in the well. The water-level reference point usually is the top of the well casing. Constant-head tests are only suitable for permeable soils such as sands and gravels. Figure 5.2-3 is a schematic of a constant-head test in a monitoring well, showing the measurements needed.

5.2-3.3.1 Requisite Data

In order to calculate the hydraulic conductivity, the following information should be obtained and recorded:

H - static water level, measured prior to the start of the test.

r - radius of the riser pipe.

L - ....
the length of the zone below the casing in a borehole or the length of the screened interval in a monitoring well including the full distance from the bottom to the top off he filter pack.

$(Q, Q_2,...Q_n)$ - flow measurements at various times (t).

$(X, X_2,...X_n)$ - water-level measurements at various times (t).

5.2-3.3.2 General Test Methods.

(a) Constant Flow

The constant flow rate required to maintain a selected excess head elevation has to be experimentally determined, and then maintained for a short period of time. Generally, a flow meter is connected to the pump discharge line that goes into the well to monitor the flow. It is important that the flow meter be calibrated, especially when low flows are used. The rate of injection should begin low and systematically be increased until a steady rate of flow is established. In some cases an anti-surge device should be placed in the supply line near the pressure gauge to obtain steady flow readings. The water level should be closely monitored at some reference point, preferably at or near the top of the casing.

(b) Duration of the Test

The test should be run until a steady flow rate is maintained for at least 15 minutes to one-half hour.

5.2-3.3.3 Test Procedures for Boreholes and Monitoring Wells.

The procedure described below applies to boreholes. For monitoring wells only Steps 3 and 4 are necessary.

1. Advance casing to the desired depth

2. Carefully wash out all the material to the bottom of the casing until the wash water remains clear. The water level should be maintained at or above the static water level to prevent squeezing of soil into the casing. This is particularly important during removal of the drilling rods. Measure the depth of the hole to determine if a void was created below the bottom of the casing.

If an open-hole test is desired, bump or pull back the casing to the desired depth.

3. Measure the static water level from the top of the casing.

4. Fill the riser with clean water and maintain the water-level at the top of the riser, or at some fixed elevation, by pumping water in at the experimentally determined, appropriate constant rate. The volume of water entering the casing should be measured with a flow meter and recorded at regular time intervals, such as every minute, to determine if a stable flow rate has been achieved and is being maintained. If the target excess head elevation is below the top of the casing and is not visually confirmable, water-level measurements should also be recorded each time the flow is measured. An example of a field form for recording constant-head test data is shown in Figure 5.2-4.

5.2-4 DATA ANALYSIS

Several methods are available for analyzing data obtained from in-situ hydraulic conductivity tests. Most methods incorporate graphical techniques, such as semi-log and log-log plots, to evaluate the data and select values for the calculations.

When evaluating these tests, the calculated hydraulic conductivity should be compared to an expected hydraulic conductivity based on the formation characteristics. (See Table 5.2-1.) Potential sources of error that can affect in-situ hydraulic conductivity tests include:

- Leaky casing or riser joints
- A low permeability skin on the borehole wall formed during drilling
- Uncertainty about the initial head
- Failure to allow the pressure transducer to stabilize
- Stress release around the borehole
- Incorrect readings
- Bridging of seals
- Entrapped air in the sandpack or formation
- Anisotropy of the formation
- Sandpack or screen permeability limitations
- Partial-penetration effects (saturated zone within the aquifer is not fully screened)
- Fractures
- Multi-phase fluids

The analysis of well or borehole hydraulic conductivity test data is based on modifications of the Thiem equation for steady-state conditions and the Theis equation for transient conditions. A few of the more commonly used analytical methods are summarized in this section. Inherent in all these methods are several simplifying assumptions concerning the aquifer properties (i.e., homogeneity, isotropy) and the test methods (instantaneous water-level change). When selecting a particular analytical method, it is important to consider the basic assumptions that underlie the mathematical expressions. In many cases it may be advisable to evaluate the data using several methods and examine the range of hydraulic conductivities that are obtained. When reporting a calculated in-situ hydraulic conductivity, the analytical method(s) used should always be referenced.

5.2-4.1 Analysis of Variable Head Test Data

In this section three analytical methods are presented that are commonly used to evaluate variable head test data. Additionally, a large number of methods developed for specialized conditions can be found in the literature. More sophisticated analytical methods than those discussed here may need to be applied under certain test conditions. In particular, the reader may want to apply the method of Bouwer and Rice (1976) for unconfined aquifers with wells that are either partially or completely penetrating the aquifer.

5.2-4.1.1 Hvorslev Time-lag Method

The Hvorslev method (Hvorslev, 1951) is based on a modification of the Thiem equation for steady-state flow. This method includes the following assumptions or conditions:

- The aquifer has unconfined conditions
- The aquifer is homogeneous and isotropic
- The aquifer has infinite areal extent
- The soil and water are incompressible
- Steady-state conditions
- The change in water level is instantaneous
- The test zone partially or fully penetrates the aquifer
- Effects of aquifer storage are assumed to be small and are ignored

The Hvorslev method is based on the following equation:

$$K = \frac{r^2 \ln(mL/R)}{2LT_o}$$

where,

K = hydraulic conductivity (length/time)
r = radius of riser or casing (length)
m = a transformation ratio to allow for some anisotropy in the vertical direction (dimensionless)
where,

$$m = \sqrt{K_h/K_v}$$

and,

K_h = horizontal hydraulic conductivity (length/time)
K_y = vertical hydraulic conductivity (length/time)

L = length of test zone (length)
R = effective radius of borehole or test zone (length)
T_o = lag time value, or the time at which $\ln(h/H_o)$ equals 0.37 on the head versus time data plot (time)

The value of T_o is determined as follows:

The excess head (h), normalized by dividing by the initial excess head (H_o), is plotted on the log scale against corresponding values of time (t) on the arithmetic scale of semi-log paper. The value of T_o is determined graphically as that value where the normalized head equals 0.37, as shown on Figure 5.2-5.

If the head versus time data deviates significantly from a linear plot, it may indicate bad test data or that the assumptions of the equation are not met. In this case, this method will not provide a reliable value for hydraulic conductivity.

Hvorslev developed this method for a variety of borehole or well configurations by including a "shape factor" in the equation. Figure 5.2-6 presents the borehole or well geometry for various shape factors (page 1 of 2) and their corresponding equations (page 2 of 2).

5.2-4.1.2 Bouwer and Rice Method

A method of analysis quite similar to that of Hvorslev's was developed by Bouwer and Rice (1976). Their equation for calculating hydraulic conductivity is identical to the Hvorslev equation except that the term ln(mL/R) is replaced by $\ln(r_e/R)$. Thus the equation is:

$$K = \frac{r_c^2 \ln(r_e/R)}{2Lt} \ln \frac{Y_o}{Y_t}$$

where,

K = hydraulic conductivity (length/time)
L = length of the test zone (length)
r_c = casing radius (length)
r_e = effective horizontal radius over which the instantaneous slug (Ho) is dissipated (length)
R = radius of borehole in test zone (length)
t = selected time since the slug was initiated (time)
Y_o = initial (t = 0) change in head (length)
Y_t = value of excess head (h) at selected time (t) (length)

The assumptions or conditions that apply to the Hvorslev method also apply to this method. The benefit of this technique is that the calculated values are based on a more vigorous estimate of the radius of influence of the test than those derived from the Hvorslev equation. This appraisal is based on the fact that instead of using a best estimate of the effective radius of the borehole or test zone, as the Hvorslev method does, Bouwer and Rice have developed a graphical procedure to calculate the effective distance from the borehole that is affected by the slug.

The graphical procedure involves determining the values of two coefficients (A and B) that appear as separate curved plots in Figure 5.2-7. These values, which are functions of the value of L/R that is specific to a well geometry, are used in the following equation to derive ln (r_e/R):

$$\ln (r_e/R) = \left[\frac{1.1}{\ln(H/R)} + \frac{A+B \ln [(D-H)/R]}{L/R} \right]^{L}$$

where,

A = a coefficient that is a function of (dimensionless)
B = a second coefficient that is a function of L/R (dimensionless)
r = effective horizontal radius (length)
H = distance from the water table to the bottom of the open test zone of the well (length)
L = length of the test zone (length)
D = saturated aquifer thickness (length)
R = radius of borehole in test zone (length)

In applying the above equation, Bouwer and Rice (1976) determined that the following conditions should be observed.

1) If 1n [D-H/R] is greater than 6, this term should be set equal to 6 in the above equation for determining ln (r_e/R).

2) If D equals H (implying that the open test zone fully penetrates the aquifer), the following equation should be used to determine ln (r_e/R):

$$\ln (r_e/R) = \left[\frac{1.1}{\ln(H/R)} + \frac{c}{L/R} \right]^{-1}$$

where,

c = a third coefficient that is a function of L/R (dimensionless)

and, all other terms are as previously defined.

In Figure 5.2-7, if the open test zone fully penetrates the aquifer being tested, only the "C" curve is read.

To implement this method, the field data are plotted as h on the log scale versus t on the arithmetic x-axis. A best fit straight line is drawn through the data points. Figure 5.2-7 is consulted to obtain the coefficients necessary to compute 1ln (r_e/R). The value of Y_o is determined by the intersection of the fitted straight line with the zero point on the X-axis. For a selected time (t), the corresponding value of Y_t on the Y-axis is read. All of these values are substituted into Bouwer and Rice's hydraulic conductivity equation to compute K.

5.2-4.1.3 Cooper et al. Type-Curve Matching.

Cooper et al. (1967) developed and Papadopulos et al. (1973) extended a type-curve matching method, based on the Theis equation, with the following assumptions or conditions:

- The aquifer is confined
- The aquifer is homogenous and isotropic
- Aquifer has infinite horizontal extent
- The change in water level is instantaneous
- Transient flow conditions (non-steady state) exist in the immediate proximity of the well
- The well fully penetrates the aquifer
- Aquifer can have limited vertical extent
- The aquifer has a uniform aquifer thickness

The values for the transmissivity (T) and hydraulic conductivity (K) can be calculated from the equations:

$$T = \frac{r_c^2}{t} (Tt/r_c)^2 \quad \text{and} \quad K = T/b$$

where,

T = transmissivity near the well (length squared/time)
Tt/r_c^2 = a time parameter: value is usually selected as 1.0 on the type-curve overlay at the match point
r_c = radius of the casing or riser (length)
t = time determined from match point (time)
K = hydraulic conductivity near the well (length/time)
b = aquifer thickness (length)

This method involves plotting the head and time data on semi-log paper and determining the best data fit to one in a family of type-curves that are plotted at the same scale. An example of the type-curves is shown on Figure 5.2-8. The normalized head values are plotted on the vertical, arithmetic scale, and the corresponding time values are plotted on the horizontal, log scale. The field data curve is then superimposed on the type-curve set. With the arithmetic axes coincident, the data plot is translated horizontally to a position where the field plot best fits the type-curve. Once the match point is determined, the time value (t) is read off the plot. Typically, a value of 1.0 is chosen for Tt/r_c^2 to simplify the calculation.

Transmissivity (T) is then calculated by solving the above equation in terms of r and t units. The value for hydraulic conductivity can be calculated by dividing the calculated transmissivity by the aquifer thickness.

5.2-4.1.4 Nguyen and Pinder Slug Test Method.

The Nguyen and Pinder method (Nguyen and Pinder, 1984) incorporates factors that account for the effects of wellbore storage and partially penetrating wells. Although it is a little more complex than the other methods that have been described, the Nguyen and Pinder method is especially suitable for conditions of low hydraulic conductivity where wellbore storage effects can be a problem. The following assumptions are inherent in this method:

- o The aquifer is either confined or unconfined conditions
- o The aquifer is homogeneous and isotropic
- o Aquifer has infinite areal extent
- o Steady-state conditions must exist around the well
- o The change in water level is instantaneous
- o A well either fully or partially penetrates the aquifer

This method utilizes a semi-log plot of the head (dh/dt) versus inverse time data (1/t), similar to the Hvorslev semi-log method. In addition, a log-log plot of (h/H_o) versus time data (t) is prepared. The slopes of these plots, C_3 for the log-log and C_4 for the semi-log plots respectively, are used to calculate the hydraulic conductivity according to the Nguyen and Pinder equation:

$$K = \frac{R2C_3}{4C_4 L}$$

where,

K = hydraulic conductivity near the well (length/time)
R = radius of the wellbore (length)
C_3 = value obtained from slope of semi-log plot (length/time)
C_4 = value obtained from slope of log-log plot (length)
L = test zone length (length)

5.2-4.2 Analysis of Constant-Head Test Data

The analysis of constant-head test data is based on a modification of Darcy's Law: Q = KA(dh/dl), described in Section 5.2-2. The analytical equation presented here requires the following simplifying assumptions:

- o The aquifer is confined
- o The aquifer is homogenious and isotropic
- o The well screen is not at the upper or lower aquifer boundary
- o There is a constant flow rate of water into or from the well

The following equation (Hvorslev, 1951) can be used to calculate the hydraulic conductivity (K) from a constant-head test when the screened section is installed in uniform soil away from soil boundaries (Figure 5.2-6, Case G):

$$K = \frac{Q_S \ln \left[\frac{L}{2r} \sqrt{1 + \frac{L^2}{r^2}} \right]}{2\pi L h}$$

where,

K = hydraulic conductivity (length/time)
Q_S = stabilized flow rate required to maintain a constant head (length cubed/time)
L = test zone length (length)
r = radius of riser or casing (length)
h = excess head, as height above static water-level (length)

Other well/aquifer geometries and associated equations for computing hydraulic conductivity are given in Figure 5.2-6 (page 2 of 2). In situations where the top of the well casing is not the established constant head elevation during the test, as shown in Figure 5.2-3, measurements of water level must be made to maintain a constant head. The measured distance, x, is subtracted from H to determine h; the excess head, as depicted in Figure 5.2-4.

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SECTION 5.2
IN-SITU HYDRAULIC CONDUCTIVITY TESTS

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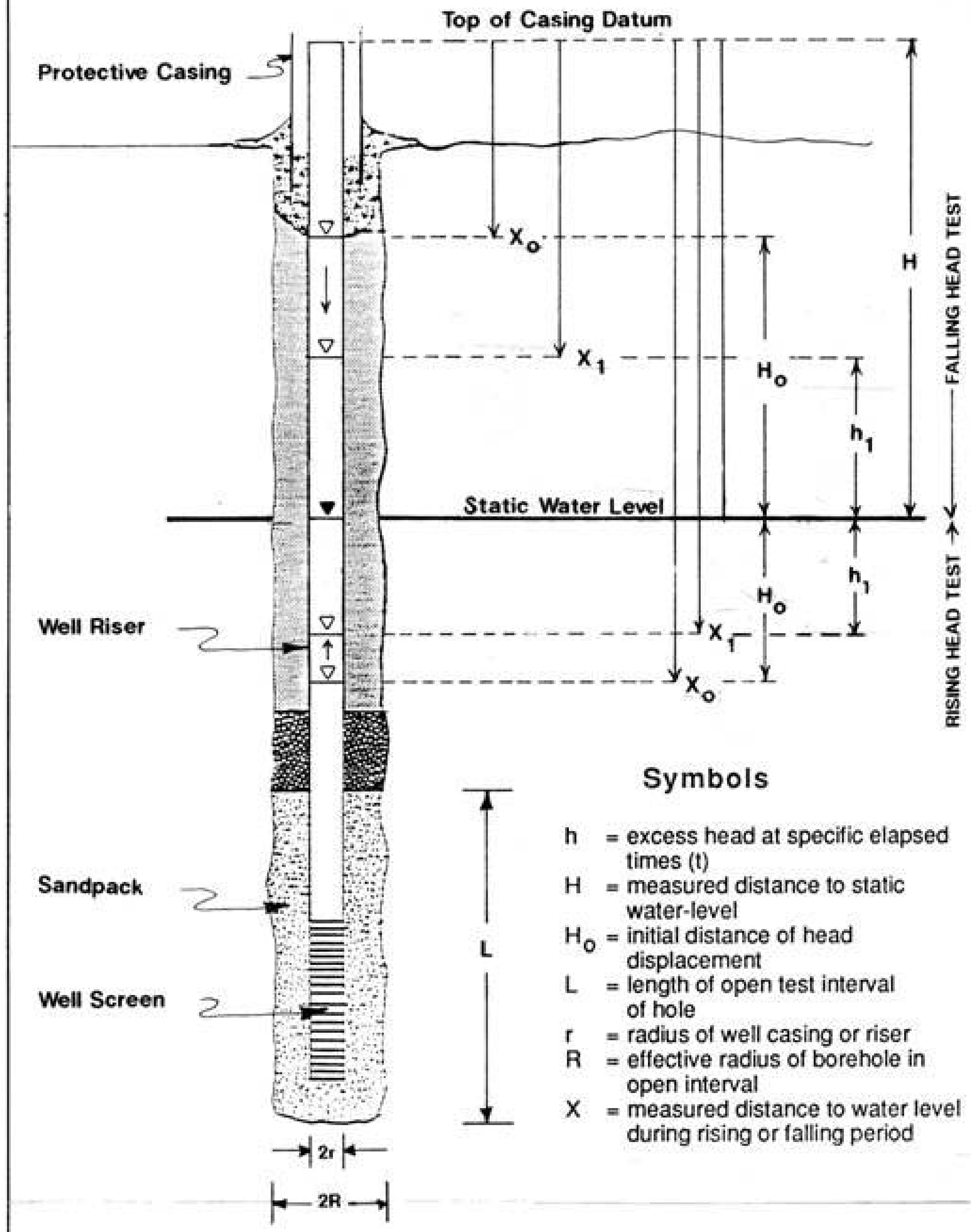


Figure 5.2-1

Source: MADEP

Well Construction Features and Measurement Configurations for Variable-head Tests.

BOREHOLE PERMEABILITY TEST
Variable-head Test

BORING NO. ________ WELLPOINT ☐ STANDPIPE ☐ TEST NO. ________

TYPE OF TEST: FALLING HEAD ☐ RISING HEAD ☐

PROJECT ________ SITE/LOCATION ________

INSPECTOR ________ DATE ________ CHECKED BY ________ DATE ________

TIME ________ GROUND ELEVATION ________ REFERENCE ELEVATION ________

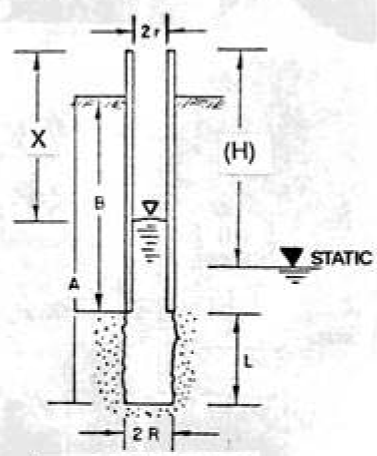
CASING I.D. ________ CASING O.D. ________

DEPTH OF BORING (A) ________ DEPTH OF TOP OF TEST SECTION (B) ________

DEPTH OF GROUNDWATER TABLE (H) ________ LENGTH OF TEST SECTION (L) ________

TYPE OF MATERIAL IN TEST ZONE (USC OR OTHER) ________

COMMENTS ________



h = H-X (falling head)
or
= X-H (rising head)

H_0 = $H-X_0$ (falling head)
or
X_0-H (rising head)

X_0 = X at t=0

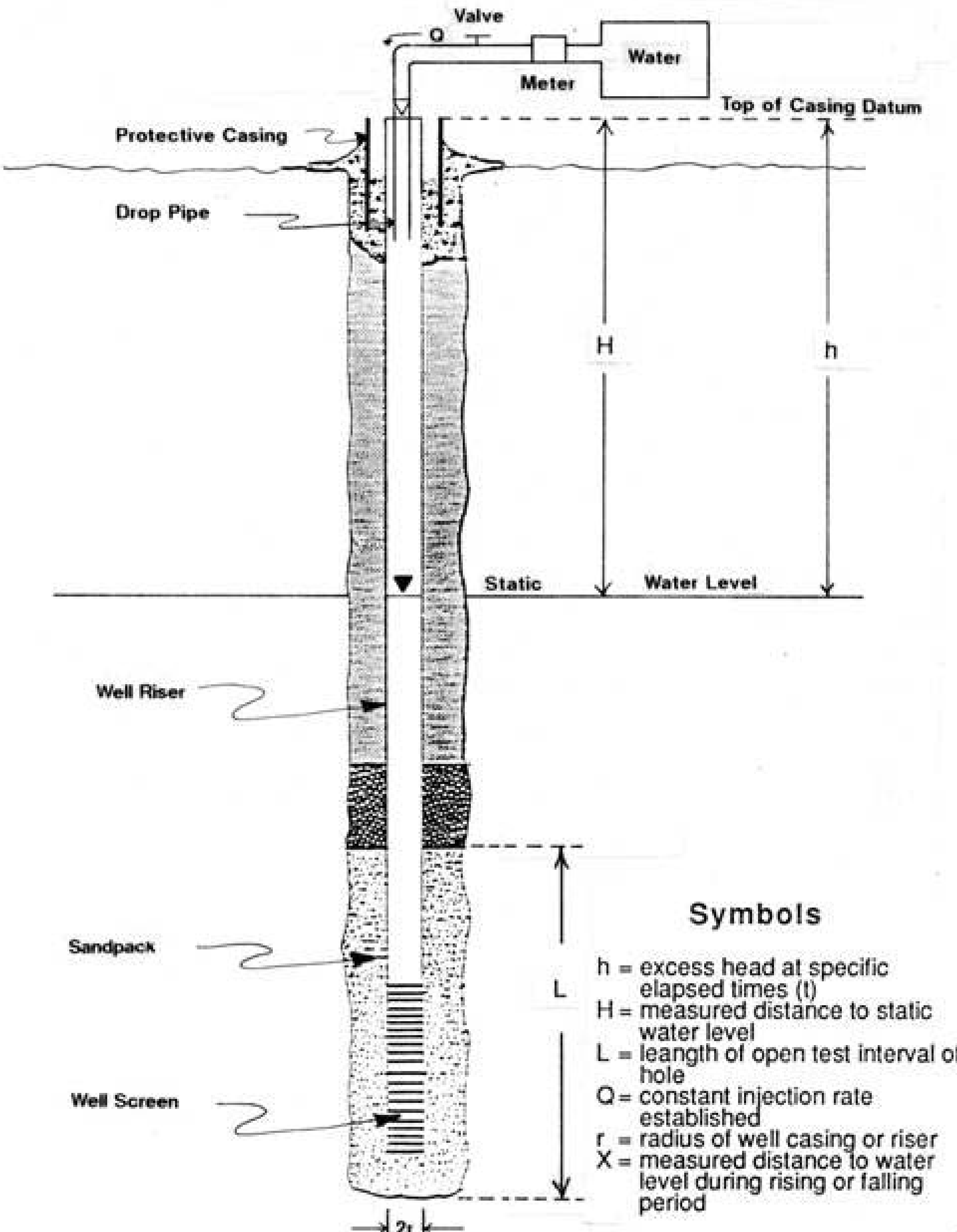
A, B, H&L are defined above

TIME	ELAPSED TIME (t)	h/H_o	WATER DEPTH (x)	ACTIVE HEAD (h)
	0	1.0		

Source: MADEP

Figure 5.2-2

Example of a Field Form for Variable-head Tests.



Source: MADEP

Figure 5.2-3

Well Construction Features and Measurement Configurations for Constant-head Tests.

BOREHOLE PERMEABILITY TEST
Constant-head Test

BORING NO. ________ WELLPOINT ☐ STANDPIPE ☐ TEST NO. ________

PROJECT ________ SITE/LOCATION ________

INSPECTOR ________ DATE ________ CHECKED BY ________ DATE ________

TIME ________ GROUND ELEVATION ________ REFERENCE ELEVATION ________

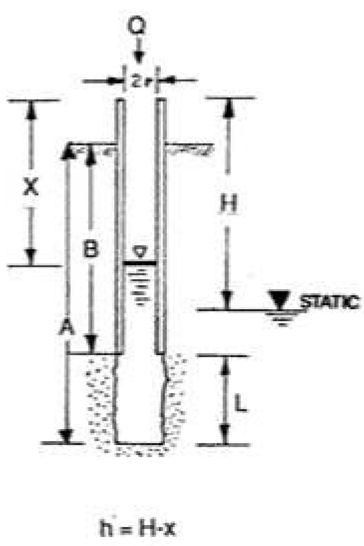
CASING ID ________ CASING O.D. ________ FLOW METER NO. ________

DEPTH OF BORING (A) ________ DEPTH OF TOP OF TEST SECTION (B) ________

DEPTH OF GROUNDWATER TABLE (H) ________ LENGTH OF TEST SECTION (L) ________

TYPE OF MATERIAL IN TEST ZONE (USC OR OTHER) ________

COMMENTS ________



h = H-x

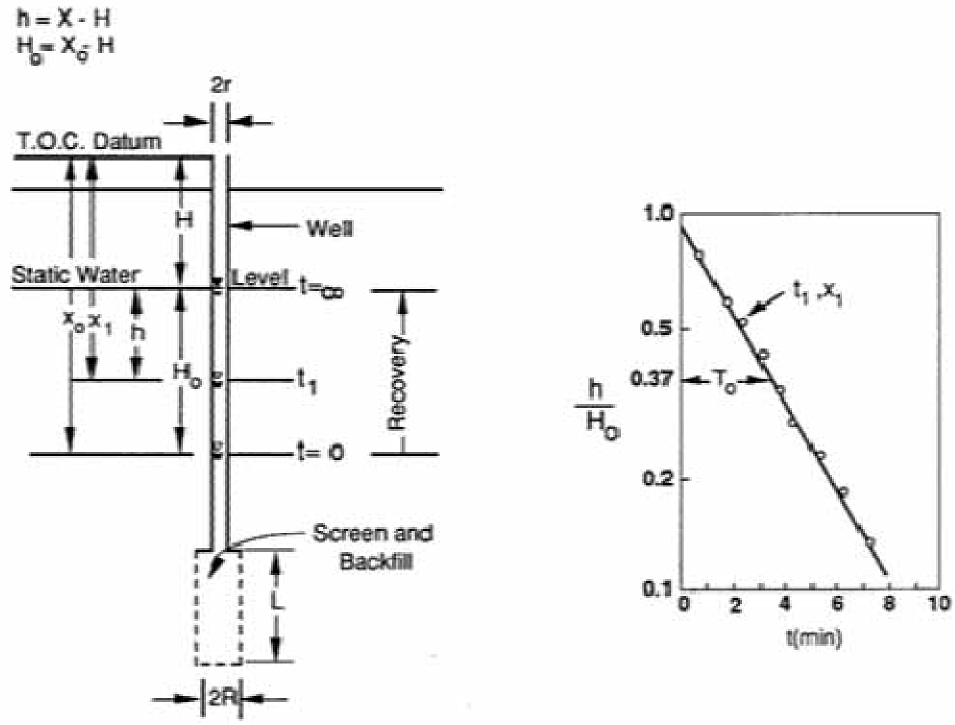
A, B, H&L are defined above

ELAPSED TIME (t) (min)	FLOWMETER READINGS (gallons)	INJECTION RATE (Q) (gal/min)	WATER DEPTH (X)	ACTIVE HEAD (h)

Figure 5.2-4

Source: MADEP

Example of a Field Form for Constant-head Tests.



(a) Test Conditions

(a) Data Plot

Symbols

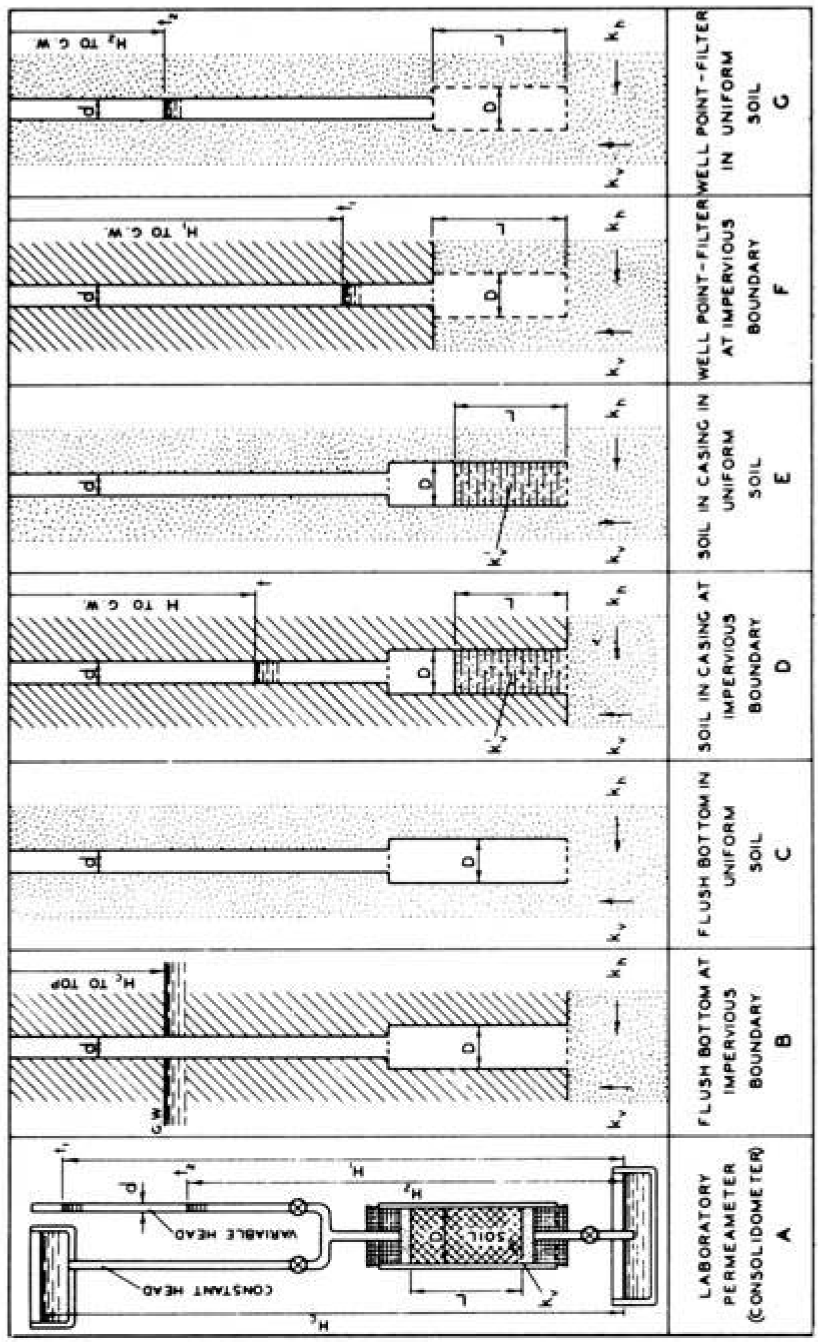
- h = excess head at specfiic elapsed times (t)
- H = initial distance of head displacement
- L = length of open test interval of hole
- r = radius of well casing or riser
- R = effective radius of borehole in open interval
- t = elapsed time corresponding to x values
- T_o = lag-time value at h/H_o = 0.37
- X = measured distance to water level during rising or falling period

T_o = normalized water level measurement at a specific time(t)

Source: After Freeze and Cherry (1979)

Figure 5.2-5

Basic Hvorslev Time-log Method for In-situ Head Tests.



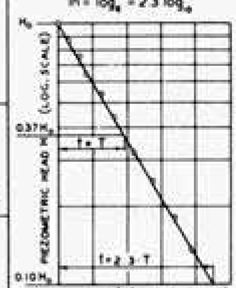
Source: Hvorslev (1951)

Figure 5.2-6
Page 1 of 2
Hvorslev Shape Factors for Hydraulic Conductivity Testing for Various Borehole Conditions.

CASE	CONSTANT HEAD	VARIABLE HEAD	BASIC TIME LAG
A	$k_v = \frac{4 \cdot q \cdot L}{\pi \cdot D^2 \cdot H_c}$	$k_v = \frac{d^2 \cdot L}{D^2 \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_v = \frac{L}{t_2 - t_1} \ln\frac{H_1}{H_2}$ FOR $d = D$	$k_v = \frac{d^2 \cdot L}{D^2 \cdot T}$ $k_v = \frac{L}{T}$ FOR $d = D$
B	$k_m = \frac{q}{2 \cdot D \cdot H_c}$	$k_m = \frac{\pi \cdot d^2}{8 \cdot D \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_m = \frac{\pi \cdot D}{8 \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ FOR $d = D$	$k_m = \frac{\pi \cdot d^2}{8 \cdot D \cdot T}$ $k_m = \frac{\pi \cdot D}{8 \cdot T}$ FOR $d = D$
C	$k_m = \frac{q}{2.75 \cdot D \cdot H_c}$	$k_m = \frac{\pi \cdot d^2}{11 \cdot D \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_m = \frac{\pi \cdot D}{11 \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ FOR $d = D$	$k_m = \frac{\pi \cdot d^2}{11 \cdot D \cdot T}$ $k_m = \frac{\pi \cdot D}{11 \cdot T}$ FOR $d = D$
D	$k_v' = \frac{4 \cdot q \left[\frac{\pi}{8} \cdot \frac{k_v'}{k_h} \cdot \frac{D}{m} + L\right]}{\pi \cdot D^2 \cdot H_c}$	$k_v' = \frac{d^2 \left[\frac{\pi}{8} \cdot \frac{k_v'}{k_h} \cdot \frac{D}{m} + L\right]}{D^2 \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_v = \frac{\frac{\pi}{8} \cdot \frac{D}{m} + L}{t_2 - t_1} \ln\frac{H_1}{H_2}$ FOR $k_v' = k_v$, $d = D$	$k_v' = \frac{d^2 \left[\frac{\pi}{8} \cdot \frac{k_v'}{k_h} \cdot \frac{D}{m} + L\right]}{D^2 \cdot T}$ $k_v = \frac{\frac{\pi}{8} \cdot \frac{D}{m} + L}{T}$ FOR $k_v' = k_v$, $d = D$
E	$k_v' = \frac{4 \cdot q \left[\frac{\pi}{11} \cdot \frac{k_v'}{k_h} \cdot \frac{D}{m} + L\right]}{\pi \cdot D^2 \cdot H_c}$	$k_v' = \frac{d^2 \left[\frac{\pi}{11} \cdot \frac{k_v'}{k_h} \cdot \frac{D}{m} + L\right]}{D^2 \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_v = \frac{\frac{\pi}{11} \cdot \frac{D}{m} + L}{t_2 - t_1} \ln\frac{H_1}{H_2}$ FOR $k_v' = k_v$, $d = D$	$k_v' = \frac{d^2 \left[\frac{\pi}{11} \cdot \frac{k_v'}{k_h} \cdot \frac{D}{m} + L\right]}{D^2 \cdot T}$ $k_v' = \frac{\frac{\pi}{11} \cdot \frac{D}{m} + L}{T}$ FOR $k_v' = k_v$, $d = D$
F	$k_h = \frac{q \cdot \ln\left[\frac{2mL}{D} + \sqrt{1 + \left(\frac{2mL}{D}\right)^2}\right]}{2 \cdot \pi \cdot L \cdot H_c}$	$k_h = \frac{d^2 \cdot \ln\left[\frac{2mL}{D} + \sqrt{1 + \left(\frac{2mL}{D}\right)^2}\right]}{8 \cdot L \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_h = \frac{d^2 \cdot \ln\left(\frac{4mL}{D}\right)}{8 \cdot L \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ FOR $\frac{2mL}{D} > 4$	$k_h = \frac{d^2 \cdot \ln\left[\frac{2mL}{D} + \sqrt{1 + \left(\frac{2mL}{D}\right)^2}\right]}{8 \cdot L \cdot T}$ $k_h = \frac{d^2 \cdot \ln\left(\frac{4mL}{D}\right)}{8 \cdot L \cdot T}$ FOR $\frac{2mL}{D} > 4$
G	$k_h = \frac{q \cdot \ln\left[\frac{mL}{D} + \sqrt{1 + \left(\frac{mL}{D}\right)^2}\right]}{2 \cdot \pi \cdot L \cdot H_c}$	$k_h = \frac{d^2 \cdot \ln\left[\frac{mL}{D} + \sqrt{1 + \left(\frac{mL}{D}\right)^2}\right]}{8 \cdot L \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ $k_h = \frac{d^2 \cdot \ln\left(\frac{2mL}{D}\right)}{8 \cdot L \cdot (t_2 - t_1)} \ln\frac{H_1}{H_2}$ FOR $\frac{mL}{D} > 4$	$k_h = \frac{d^2 \cdot \ln\left[\frac{mL}{D} + \sqrt{1 + \left(\frac{mL}{D}\right)^2}\right]}{8 \cdot L \cdot T}$ $k_h = \frac{d^2 \cdot \ln\left(\frac{2mL}{D}\right)}{8 \cdot L \cdot T}$ FOR $\frac{mL}{D} > 4$

NOTATION

D = DIAM. INTAKE, SAMPLE, CM
d = DIAMETER, STANDPIPE, CM
L = LENGTH, INTAKE, SAMPLE, CM
H_c = CONSTANT PIEZ. HEAD, CM
H_1 = PIEZ. HEAD FOR $t = t_1$, CM
H_2 = PIEZ. HEAD FOR $t = t_2$, CM
q = FLOW OF WATER, CM^3/SEC.
t = TIME, SEC.
T = BASIC TIME LAG, SEC.
k_v' = VERT. PERM. CASING, CM/SEC.
k_v = VERT. PERM. GROUND, CM/SEC.
k_h = HORZ. PERM. GROUND, CM/SEC.
k_m = MEAN COEFF. PERM., CM/SEC.
m = TRANSFORMATION RATIO
$k_m = \sqrt{k_h \cdot k_v}$ $m = \sqrt{k_h / k_v}$
$\ln = \log_e = 2.3 \log_{10}$



DETERMINATION BASIC TIME LAG T

ASSUMPTIONS

SOIL AT INTAKE, INFINITE DEPTH AND DIRECTIONAL ISOTROPY (k_v AND k_h CONSTANT) - NO DISTURBANCE, SEGREGATION, SWELLING OR CONSOLIDATION OF SOIL - NO SEDIMENTATION OR LEAKAGE - NO AIR OR GAS IN SOIL, WELL POINT, OR PIPE - HYDRAULIC LOSSES IN PIPES, WELL POINT OR FILTER NEGLIGIBLE

Source: Hvorslev (1951)

Figure 5.2-6
Page 2 of 2
Hvorslev Equations for Hydraulic Conductivity Testing for Various Borehole Conditions.

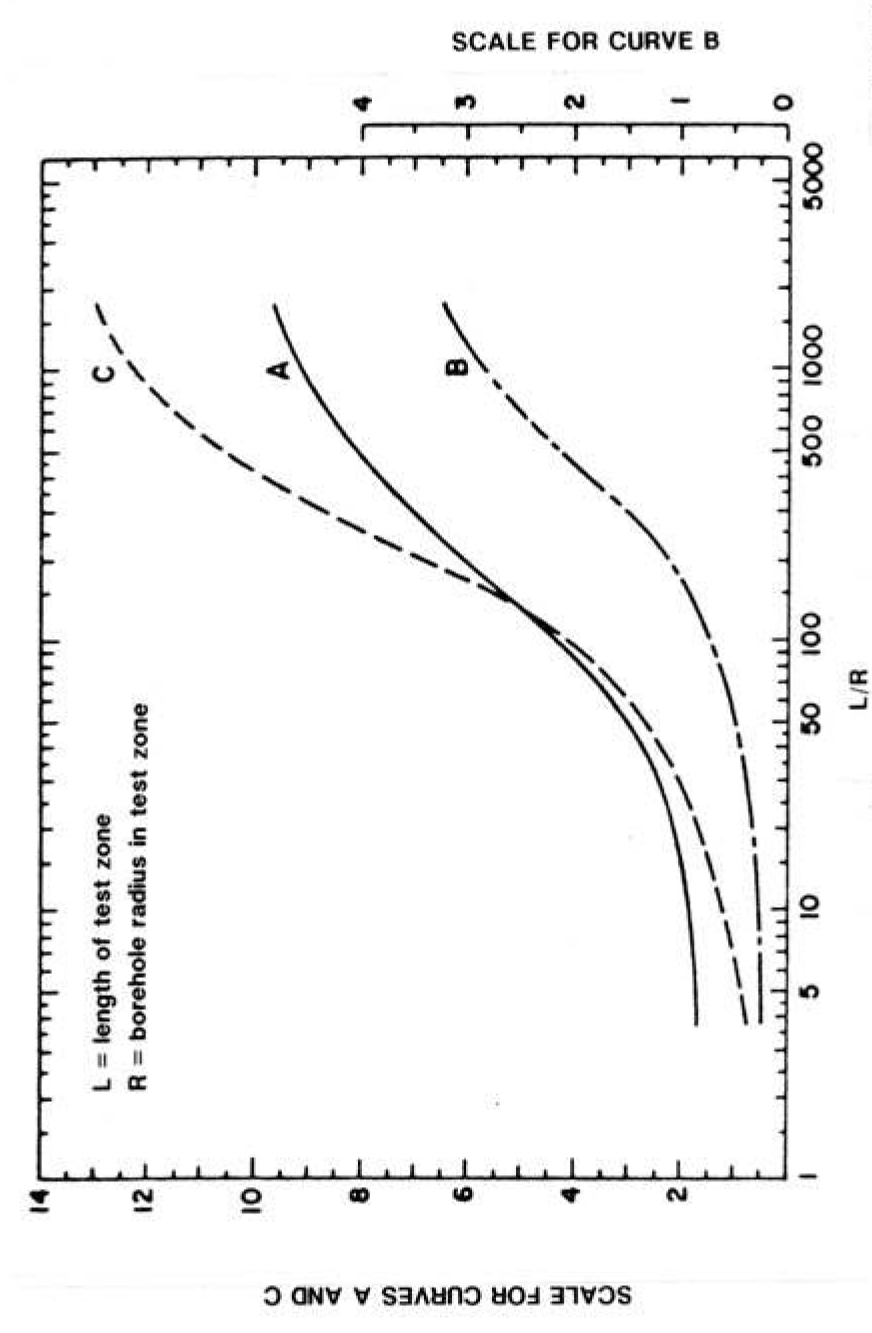
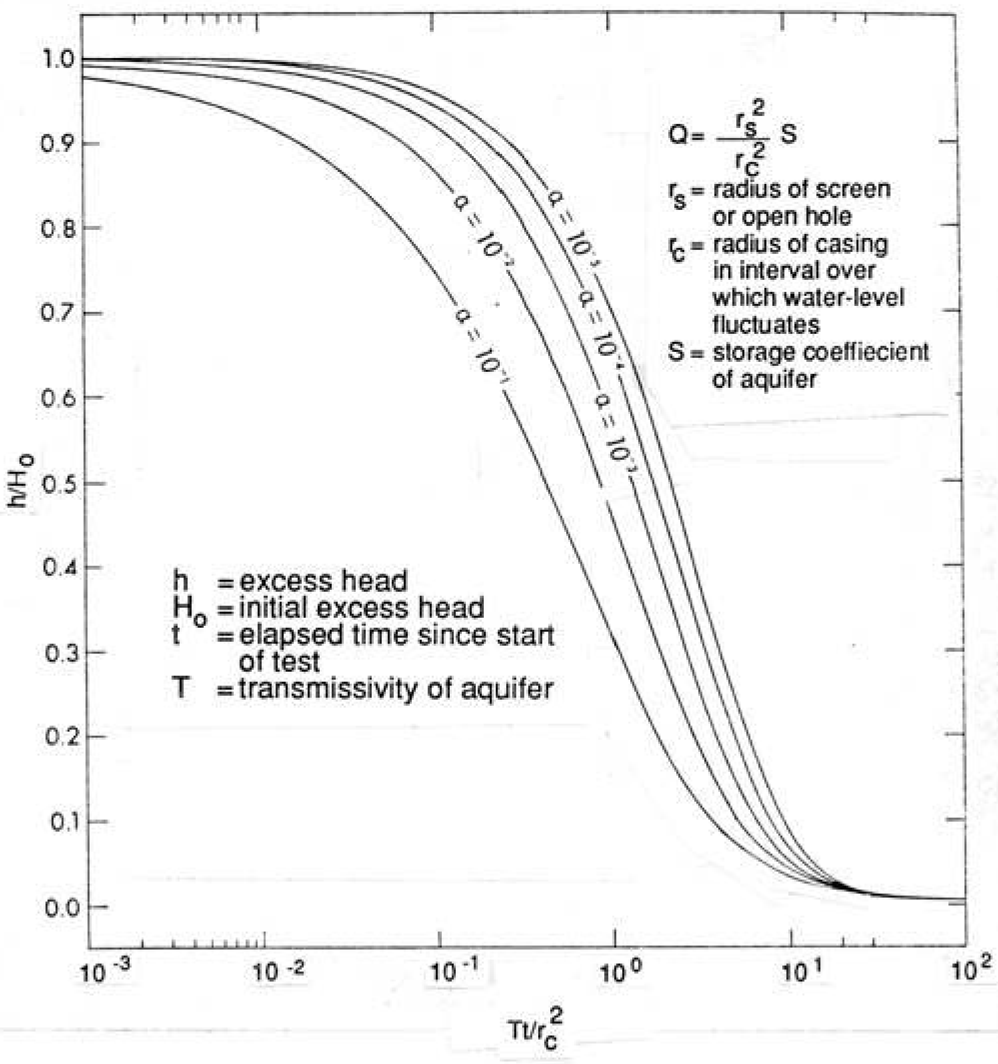


Figure 5.2-7

Graphic Determination of Bouwer and Rice's Coefficients for Calculating Effective Radius Term ln(r_e/R).

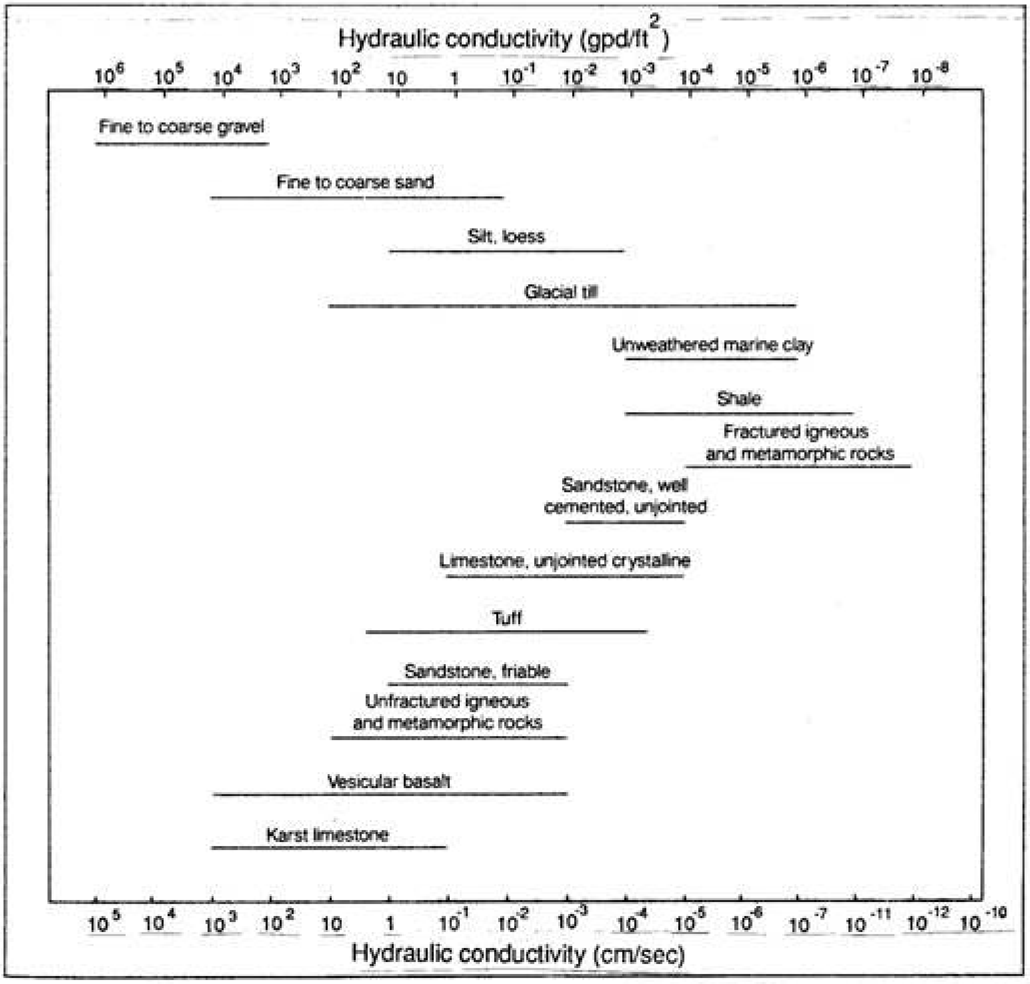
Source: Bouwer and Rice (1976)



Source: After Cooper et al. (1967)

Figure 5.2-8

Type-curves for Slug Tests of Confined Aquifer Wells, Considering Wellbore Storage.



Source: After Driscoll (1986)

Table 5.2-1

Ranges of Hydraulic Conductivity for Natural Soils and Rocks

Material	φ Porosity (%)	K Hydraulic Conductivity (cm/sec)	K Hydraulic Conductivity (ft/day)	K Permeability (darcys @ 20 c)
Granite, dense	0.3	1.7×10^{-9}	4.9×10^{-6}	2.0×10^{-6}
Granite, fractured	1.2	2.3×10^{-5}	6.6×10^{-2}	2.7×10^{-2}
Quartzite, dense	0.6	1.6×10^{-9}	4.6×10^{-6}	1.9×10^{-6}
Schist, highly-weathered, clay-rich	48	2.7×10^{-5}	7.5×10^{-2}	3.1×10^{-2}
Schist, fractured and partly weathered	5	1.2×10^{-3}	3.4	1.4
Basalt, dense	7.7	1.2×10^{-8}	3.4×10^{-5}	1.4×10^{-5}
Tuff, friable	36	1.2×10^{-6}	3.4×10^{-3}	1.4×10^{-3}
Conglomerate, highly-lithified	17.3	4.2×10^{-7}	1.2×10^{-3}	4.9×10^{-4}
Sandstone, medium-grained	15.6	6.5×10^{-5}	1.8×10^{-1}	7.6×10^{-2}
Shale, compacted	21	3.5×10^{-9}	9.8×10^{-6}	4×10^{-6}
Limestone, dense	10.1	6.6×10^{-6}	1.9×10^{-2}	7.7×10^{-3}
Clay, marine	48.5	1.4×10^{-8}	3.9×10^{-5}	1.6×10^{-5}
Sand, medium-grained	42.9	1.6×10^{-2}	44.3	18.2
Sand, medium to coarse-grained	37.4	2.4×10^{-2}	66.9	27.5
Sand, fine-grained	40.1	1.3×10^{-3}	3.6	1.5
Silt, sandy	39.4	3.2×10^{-5}	9.2×10^{-2}	3.8×10^{-2}
Silt, loess, fine-grained	50	2.8×10^{-4}	7.9×10^{-1}	0.33
Gravel, fine-grained, some sand	32.1	7.6×10^{-2}	216	89

Note: With water at 20°C, material having one darcy permeability will have a hydraulic conductivity of 0.74 meters/day which is equivalent to 2.43 feet/day.

Source: Davis et al. (1969)

Table 5.2-2

Examples of Values for Hydraulic Conductivity, Intrinsic Permeability, and Associated Porosities

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 5.3 PUMPING TESTS

SECTION 5.3 PUMPING TESTS

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SECTION 5.3 PUMPING TESTS

5.3-1 PURPOSE

This Standard Reference (SR) describes various applications, design criteria, test procedures, and data interpretation methods for aquifer pumping tests. Pumping tests involve the pumping of a fluid (generally water) from a well while monitoring the water-level decline (drawdown) over time in the pumping well and surrounding observation wells.

Generally, pumping tests require a relatively large expenditure of funds, manpower and time. Failure to adequately design and execute a test program can severely compromise the data. This section is intended to provide some general procedures that should help to minimize data collection problems and errors. These procedures are meant as general guidelines only; specialized pumping test programs may require specific procedures. For example, pumping tests conducted for public water supply sources require that the test be designed and carried out in accordance with the guidelines and requirements of the Division of Water Supply. Guidelines and Policies for Public Water Systems (revised 1989) should be consulted concerning the specific test design requirements and procedures for water supply sources in Massachusetts.

5.3-2 APPLICATIONS

Until quite recently pumping tests were primarily undertaken to determine the suitability of a well and/or aquifer for water supply purposes. More recently, pumping tests have been conducted for a variety of other reasons, such as to obtain a better overall understanding of a hydrogeologic system or to design and evaluate the effectiveness of an aquifer remediation program. A list of some of the more common pumping test applications is presented below.

5.3-2.1 Water Supply Studies

- To determine sustained well yield and specific capacity.
- To determine pump sizing parameters.
- To calculate aquifer properties in order to estimate aquifer system storage, recharge rate, long-term drawdown, and potential interference with other production wells or aquifer boundaries.
- To define wellhead protection zones and recharge areas for aquifer protection purposes.

5.3-2.2 Hydrogeologic Studies

- To define aquifer characteristics such as transmissivity, hydraulic conductivity, and storativity.
- To identify local boundaries of an aquifer system.
- To provide calibration data for ground water flow models.
- To estimate dewatering requirements for excavations.
- To predict the rise in the water table as the result of a dam and associated impoundments.
- To predict the feasibility and impact of injection wells.

5.3-2.3 Contaminant Studies

- To perform chemical time-series sampling to evaluate the temporal and spatial variability of contaminants in ground water.
- To estimate capture zones of existing or proposed extraction wells and evaluate their effectiveness in intercepting and removing contaminated ground water, or non-aqueous phase liquids.
- To design remedial pumping schemes for plume containment through hydraulic controls.
- To evaluate the effectiveness of alternative remedial pumping schemes.

5.3-3 GENERAL CONCEPTS

In this section several general concepts and terms are presented that relate to the design and evaluation of pumping tests. Individuals involved in the design, implementation and analysis of pumping test data must have a working knowledge of the fundamentals of ground water hydrology. For additional information, the reader should consult one of the many texts covering well hydraulics such as Bear (1979), Driscoll (1986), Fetter (1988), Freeze and Cherry (1979), and Todd (1980).

5.3-3.1 Types of Aquifers

5.3-3.1.1 Confined Aquifer

A confined aquifer occurs when the ground water is confined by an overlying, less permeable geologic unit under pressure that is greater than atmospheric pressure. As shown on Figure 5.3-1, a confined aquifer is bounded above and below by relatively impermeable strata. The level of the water in a well that penetrates the confined aquifer is called the potentiometric (or piezometric) surface; it represents the hydrostatic pressure level of the water in the well. By definition, the water level or hydraulic head in a confined aquifer is always at or greater than the elevation of the bottom of the upper confining layer. During a pumping test in which the aquifer remains under confined conditions, the volume of water removed from storage in the aquifer is derived from the expansion of water due to the decrease in hydrostatic pressure and the compression of the aquifer matrix; discharge is not derived from gravity drainage.

5.3-3.1.2 Unconfined Aquifer

In an unconfined aquifer the water in the aquifer is at atmospheric pressure. The upper boundary of this potentiometric surface is often referred to as the water table; it is shown on Figure 5.3-2. In an unconfined aquifer the water removed from storage during a pumping test beyond the initial few minutes of pumping is the result of gravity drainage from the saturated material. The water level change resulting from water being removed from storage may not occur instantaneously; it may show a delayed response. This phenomenon, known as delayed yield, is frequently observed in pumping tests in unconfined aquifers.

5.3-3.1.3 Leaky Aquifer

A leaky aquifer is a fully saturated (semi-confined) aquifer that is bounded above and below by a less permeable layer, one or both of which transmit water to the pumped aquifer. (As the most permeable layer does not actually leak itself, the term "leaky aquifer" encompasses the above and/or below leaky layers, called aquitards.) When pumped, the water comes from both horizontal flow of water released by pressure reduction in the permeable layer and vertical flow (leakage) downward or upward from aquitards. Figure 5.3-3 is a diagram of a leaky aquifer receiving leakage from the overlying aquitard.

5.3-3.2 Aquifer Conditions

5.3-3.2.1 Steady-state (Equilibrium) Conditions

Under steady-state flow conditions the magnitude and direction of the flow velocity at any location in the aquifer is constant with time. For such a condition to exist in an aquifer, there can be no change in the water level or potentiometric surface over time. Consequently, in order to achieve steady-state conditions during a pumping test, the rate of recharge to the aquifer must become equal to the rate of withdrawal. Although in the strictest sense this condition is rarely achieved during a pumping test of several days to several weeks, long, steady-state conditions are often assumed in situations where the changes in head over time are so small that they can be considered negligible. In practice, drawdown changes of less than about 0.1 foot over 24 hours can often be attributed to factors other than a lack of balance between discharge of the well and recharge to the aquifer.

5.3-3.2.2 Non-steady-state Conditions

Non-steady-state conditions, also called transient or non-equilibrium conditions, occur when the potentiometric surface is changing over time. In a pumping test, non-steady flow conditions occur from the start of the test until steady-state conditions are achieved. Thus, analysis of most pumping tests involves the application of only transient analytical methods (solutions).

5.3-3.3 Aquifer Properties

5.3-3.3.1 Transmissivity

Transmissivity (T) is defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. Figure 5.3-4 shows a conceptual representation of transmissivity and hydraulic conductivity (K). Transmissivity is a function of the properties of the fluid, the porous media, and the thickness of the saturated porous media. Transmissivity is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow direction. Transmissivity (T) is related to hydraulic conductivity as follows:

$$T = K\ b$$

where,

T = aquifer transmissivity (length/time)
K = average hydraulic conductivity of the saturated zone (length/time)
b = average thickness of the saturated zone (length)

The alternative English units for transmissivity are gpd/ft, which can be reduced to ft^2/day by dividing by 7.48.

The concept of aquifer transmissivity assumes horizontal flow through the aquifer that may be violated where vertical hydraulic gradients and vertical hydraulic conductivity are larger than these same components horizontally. Because transmissivity is directly proportional to both the aquifer thickness (b) and the hydraulic conductivity (K), it differs from one aquifer to another and from place to place within a single aquifer.

5.3-3.3.2 Storativity and Specific Yield

Storativity, also called the storage coefficient, is a dimensionless aquifer parameter. It is defined as the volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head. Figure 5.3-5 is an illustration of water released from storage in confined and unconfined aquifers resulting from a unit decline in head. The magnitude of the storage coefficient depends on aquifer type (i.e., whether it is confined or unconfined). In a confined aquifer the aquifer remains saturated and the amount of water released during pumping is related to the thickness or the aquifer, compressibility of the aquifer structure and the expansion of the pore water. Consequently, the storage coefficient is related to the elasticity of the aquifer material and that of the fluid. Storage coefficients for confined aquifers range from 0.001 to 0.00001 (Walton, 1988).

In unconfined aquifers, the primary source of water is from gravity drainage of the pore spaces due to a decline in head. This dimensionless storage parameter is called the specific yield; it is related to the effective porosity of the porous media. In pumping-test analyses of unconfined aquifers, the terms storage coefficient and specific yield are often used synonymously. Values for specific yield normally range from 0.01 to 0.3 (Walton, 1988). For crystalline rock aquifers, storativity may be as low as the 10^{-3} range. The storage coefficient and specific yield must be quantified to determine the amount of water available from an aquifer.

5.3-3.4 Terminology

The concepts relating to the description of a natural ground water flowfield caused by a pumping well are taken from Morrissey (1987). Morrissey's terminology that accompanies his figures will be used throughout this chapter.

5.3-3.4.1 Cone of Depression

The cone of depression is the geometric solid included between the water table or other potentiometric surface after a well has begun discharging and the hypothetical position the water table or other surface would have had if there had been no discharge by the well (Theis, 1935). This depression in the water table or other potentiometric surface can be visualized as a flared, cone-shaped geometric solid (see Figures 5.3-1, -2 and -3). The maximum drawdown occurs at the pumping well. For a given aquifer, the cone of depression increases in depth and extent with increasing time until steady-state flow is reached. Drawdown at any point at a given time is directly proportional to the pumping rate and inversely proportional to aquifer transmissivity and aquifer storativity, with transmissivity exerting the greater influence.

5.3-3.4.2 Area of Influence

The area of influence of a pumping well is the land that directly overlies and has the same horizontal extent as the part of the water table or other potentiometric surface that is perceptibly lowered by the withdrawal of water (Meinzer, 1923).

Ground water in porous media flows radially to a well from all directions. Under ideal aquifer conditions of homogenity and isotropy, and essentially zero natural flow gradient, ground water at any given distance from a pumping well flows at an equal rate towards the pumping well through imaginary concentric cylinders about the well (Figure 5.3-6). Under these conditions the area of influence is circular and the velocity is inversely related to the radial distance. In reality, the area of influence is elliptical but irregularities may occur due to aquifer inhomogeneity. These patterns apply to both confined and unconfined aquifers.

The size and shape of the area of influence is determined by the slope of the pre-pumping water table or potentiometric surface, by the pumping rate, by the transmissivity of the aquifer and its variations, and by the degree and distribution of vertical leakage from aquitards.

5.3-3.4.3 Zone of Contribution

The zone of contribution of a pumping well is defined by Morrissey (1987) as the volumetric portion of an aquifer from which ground water flow is diverted to a pumping well. The zone of contribution can be visualized as a three-dimensional volume of aquifer as depicted in cross-section and plan view in Figure 5.3-7. It is sometimes called the capture zone.

5.3-3.4.4 Contributing Area

The contributing area of a pumping well is defined by Morrissey (1987) as the land area that has the same horizontal extent as that part of an aquifer, or adjacent areas, from which ground water flow is diverted to the pumping well. The contributing area for a pumping well can be visualized as a two-dimensional bullet-shaped area on the land surface, as shown in Figure 5.3-7(b).

Morrissey (1987) lists a number of factors that have been shown to affect the area that contributes flow to a pumping well. Among these factors are:

- Well discharge rate and duration of pumping period.
- Aquifer transmissivity.
- Aquifer storage coefficient or specific yield.
- Proximity of the pumping well to aquifer boundaries.
- Spatial and temporal variations in aquifer transmissivity and/or storage coefficient.
- Spatial and temporal variations in aquifer recharge.
- Partial penetration by the pumping well.
- The presence of extensive confining layers.

One must be careful not to treat the contributing area and area of influence as identical. These areas can be the same only under the hypothetical circumstances where the pre-pumping water table is perfectly flat and all aquifer properties are uniform within the area of influence. When the pre-pumping water table has a gradient, as it does under nearly all natural conditions, the contributing area to the well will be distorted so that it extends a greater distance on the upgradient side and a lesser distance on the downgradient side. Figure 5.3-7, based on Morrissey (1987), illustrates this point.

The equilibrium water-table configuration and natural flow directions in the aquifer are shown in Figure 5.3-8(a). The drawdown and area of influence for steady-state pumping conditions are shown in Figure 5.3-8(b). (The area of influence is herein defined as that area where drawdowns caused by pumping are 0.1 feet or greater.) Theoretically, very small drawdowns will extend to the boundaries of the aquifer even though they might not be detectable by field measurements. The difference between the areas of influence and contribution for the hypothetical conditions portrayed are clearly shown on Figures 5.3-8(b) and (c).

5.3-3.4.5 Boundary Conditions

The presence of boundary conditions can have a major effect on the response of an aquifer to pumping. There are three basic types of aquifer boundaries that are significant to the interpretation of pumping tests: (1) impermeable boundaries, (2) constant-head boundaries, and (3) infinite boundaries. Impermeable boundaries, also known as no-flow boundaries, consist of very low permeability features, such as buried bedrock valley walls. Constant-head boundaries are sources of unlimited amounts of water; a river is a line source of constant head (see Figure 5.3-8). An infinite boundary, or open boundary, lies at a remote distance from the pumping well and does not affect the drawdown caused by a pumping well.

5.3-4 DESIGN CONSIDERATIONS

A well-conceived pumping test design will help ensure that adequate data are collected during the test to permit reliable calculations of the necessary aquifer parameters and a technically sound prediction of the long-term response of the aquifer to pumping. Recommended references covering design considerations are Stallman (1971), Kruseman and De Ridder (1983), and Walton (1988).

5.3-4.1 Objectives of the Pumping Test

It is important to clearly define the objectives of the pumping test prior to installing observation wells, pumps, or expensive instruments. The objective(s) of the pumping test, in addition to budgetary constraints, will determine the number and location of observation wells, the duration of the test, and the number and type of water samples collected for analyses during the test. If the objective of the test is merely to determine the yield of a well, then observation wells may not be required. On the other hand, if the purpose of the test is to define the zone of contribution (i.e., capture zone) around a water-supply well because of concern about contamination, the test may require the installation of a number of observation wells and a longer pumping period.

In contaminated aquifers, monitoring wells may already have been installed. Because existing monitoring wells are usually not suitable to serve as a pumping well, a new pumping well may be required to sustain a sufficient level of stress on the aquifer. Depending upon the locations and screened depths of existing wells, additional monitoring wells also may be needed for collection of useful pumping test data.

5.3-4.2 Pre-test Conceptual Model

A conceptual model of the aquifer should be developed as part of the pumping test design. The aquifer type (confined, unconfined, or leaky) and geometry should be generally, if not specifically, known prior to the test. Boundary conditions such as the location of lakes, streams, and valley walls should be considered as potential sources of recharge or diminished flux, and outlined on a map of the test area.

5.3-4.3 Pre-test Response Prediction

Prior to pumping it is often helpful to estimate the response of the aquifer to a set of assumed conditions to aid in the effective placement of observation wells, as well as to determine the test duration and anticipated drawdowns. Assumed values of aquifer parameters (i.e., hydraulic conductivity, transmissivity, and storativity) can be used in simple analytical equations to predict the gross aquifer response to pumping at a specified rate. From these estimates optimum distances and locations for monitoring wells can be selected.

5.3-4.4 Long- and Short-term Tests

If a long-term pumping test is planned, it is advisable to perform a short-term, step-drawdown test on the discharge test well to determine the most appropriate pumping rate, evaluate the well efficiency, and observe the response in the observation wells. The short-term, step-drawdown pumping test will provide an estimate of the magnitude of the drawdown and the rate of response in the pumping and observation wells during the long-term test. It is important to utilize a pumping rate that will adequately stress the system and produce a measurable response in the aquifer and observation wells. An additional consideration, when working at contaminated sites, is to minimize the amount of contaminated water that is discharged from the pumping well to reduce the problems and cost associated with treatment and disposal of the pumped water.

5.3-5 CONSTANT-RATE PUMPING TESTS AND PROCEDURES

There are two common types of aquifer pumping tests: (1) constant-rate pumping tests and (2) step-drawdown tests. These tests are discussed in this and the following subsections. The constant-rate test is discussed in more detail than the step-drawdown because much of the information presented about a constant-rate test can be applied to a step-drawdown test.

A constant-rate pumping test consists of pumping a well at a constant discharge rate for an extended period of time and measuring the water-level response in the pumping well and surrounding observation wells. A constant-rate test may last for only a few hours (short-term) or it may be conducted for a period of several days, weeks, or months (long-term). Reliable estimates of aquifer transmissivity and storativity can usually be computed from constant-rate pumping test data. Depending on the duration of the test and the conditions in the aquifer, aquifer boundaries (including leakage) and stratigraphic boundaries generally can be identified.

5.3-5.1 Test Operating Requirements

5.3-5.1.1 Selection of a Pump

Accurate control and monitoring of the pump discharge rate is essential during a pumping test. The rule of thumb is that the pumping rate should not deviate more than ±10% during the test (Stallman, 1971). Selection of the properly-sized pump will help achieve this objective. Ideally, the pump should operate at 1/2 to 3/4 of its rated capacity but not at the maximum rate, inasmuch as it is difficult to stabilize the flow at maximum capacity. A valve should be placed between the pump and the discharge line to regulate the flow. If the valve is kept partially closed, the back pressure will help the pump operate more smoothly. The proper pump size can be selected based on the results of a short-term step-drawdown test.

5.3-5.1.2 Selection of the Pumping Rate

Selection of the correct pumping rate is dependent on the objectives of the test and the aquifer conditions. In general, a constant-rate pumping test is conducted at a rate greater than the anticipated pumping rate of a water supply or extraction well in order to maximize the information collected over the relatively short test period. The maximum practical drawdown is often used to anticipate the optimum pumping rate for a given length of test. The response of the aquifer to a short-term stress is used to extrapolate the effects of long-term pumping at a reduced rate. In certain cases, such as the design of a remedial pumping program or two-phase product recovery program, use of a pumping rate similar to the anticipated rate of withdrawal is more desirable.

5.3-5.1.3 Measuring the Pump Discharge

Monitoring of the pump discharge can be performed in several ways. Selection of the most appropriate method depends on the expected pumping rate and the scope of the test. Although timed bucket measurements or flow meter measurements can be used, their range of accuracy is usually quite limited. A more reliable method of discharge measurement is the circular orifice weir method. As shown on Figure 5.3-9, a length of pipe with an orifice plate on the end is attached to the pump discharge. A small piezometric tube, called a manometer, taps into the side of this pipe and is attached to a measuring rule. The pump discharge is monitored by maintaining a specific water level in the manometer throughout the test. The height of the water level in the manometer is related to the discharge rate and the size and type of circular orifice. Tables for manometer/orifice discharge relationships can be found in the literature.

It should be pointed out that as the water level in the well declines due to pumping, the work required of the pump increases. Because of the increased lift required of the pump to discharge at the land surface, the discharge rate may decline significantly. In order to maintain a constant pumping rate, the discharge valve must be adjusted during the test to compensate for this effect. Thus, the test should begin with the control valve not fully opened.

5.3-5.1.4 Discharge

The water from the pumping test should be discharged into an area where it will not affect the pumping test results. This is especially important for pumping tests conducted in shallow, unconfined aquifers. It is important to select a discharge line with a diameter large enough to eliminate the potential for back pressure on the outlet of the orifice plate, as this will affect the manometer reading. If the pumping test water is contaminated, appropriate arrangements must be made for its storage and treatment or disposal. In some cases the discharge can be treated on-site and discharged to the ground; under other circumstances off-site disposal may be required. In some instances a DWPC or EPA permit may be required for a pump test discharge. In all cases, DEP requires that the discharge options be evaluated and that the preferred alternative be approved by the Department.

5.3-5.1.5 Observation Wells

(a) Size Considerations

Observation well diameters should be small enough to prevent time lags in the drawdown response. Generally observation wells ranging in diameter from 2- to 4-inches are used, depending on the permeability of the aquifer. Low permeability aquifers, and particularly aquitards, may require small diameter observation wells, such as 1-inch or 3/4-inch.

(b) Placement

A major factor influencing the size and rate of expansion of a cone of depression is whether an aquifer is confined or unconfined. In general, drawdown in an unconfined aquifer will expand gradually and slowly from a pumping well. By comparison, confined aquifer drawdown will occur quite rapidly, forming a comparatively steep cone of depression around a pumping well; the rate of expansion depends on the transmissivity of the aquifer.

If the aquifer is strongly anisotropic, the distance beyond which the flow can be assumed to be horizontal has been described by Walton (1988).

$$r = 2b\sqrt{K_h/K_v}$$

where,

- r = distance between observation and pumping wells (length)
- b = average thickness of the saturated zone (length)
- K_h = average horizontal hydraulic conductivity of the saturated zone (length/time)
- K_v = average vertical hydraulic conductivity of the saturated zone (length/time)

Therefore, within this proximity to the pumping well, the screened interval of the observation wells should be placed at the same elevation as the screened interval of the pumping well in order to negate the effects of vertical flow.

If confined or leaky aquifer conditions are expected, placement of two or more observation wells in vertically adjacent strata may be desirable. The horizontal placement (i.e., distance from the pumping well) of the observation wells will depend on the test objective(s) and the type of aquifer conditions. If possible, observation wells should be placed to allow for both time-drawdown and distance-drawdown calculations; they should also be located close to known or suspected aquifer boundaries to determine their characteristics.

The optimal distances that observation wells should be located from the pumping well can be examined through the application of the Theis equation, using best estimates for aquifer transmissivity and storativity. At a minimum, two close-in locations and two distant locations should be monitored. The close-in wells are generally at least 1.5 times the aquifer thickness from the pumped well if the pumped well has a short screen relative to aquifer thickness. This criterion should eliminate the need to analyze the observation water-level data with partial penetration type-curves. As a general rule, distant observation wells should be located such that, at the anticipated pumping rate, drawdowns will be greater than total fluctuations expected from other causes so as not to be masked. Usually, at least 0.5 feet of drawdown at the end of a test is desirable.

If determination of anisotropy and/or the area of influence is of interest, observation wells may be placed radially around the pumping well to define the shape and size of the cone of depression at different times during the test. If a moderate to steep potentiometric gradient (greater than approximately 0.005 ft/ft) is known to exist in a specific orientation, observation wells should be located along two perpendicular lines intersecting at the production well. One line should be aligned with the general direction of groundwater flow. If possible, the wells should be located at 1 times and 10 times the distance from the pumping well in at least three of the four directions from the well along the lines (Fetter, 1988).

In some cases, existing monitoring or domestic wells are used to monitor the water-level response during a pumping test. When reviewing data from such wells, however, the well diameter, screen length and elevations of the screened interval should be considered to determine their impact on the water-level response at the well. In addition, previous stresses on the aquifer, mounding effects, or drawdowns due to extraneous pumping offsite, must be considered.

(c) Hydraulic Communication

The degree of hydraulic response (i.e., "sluggishness") must be known at least qualitatively for each observation well to be monitored. Generally the information is available readily for most newly completed wells, but often the hydraulic communication between well and aquifer is totally unknown for older wells. Wells that respond sluggishly to rapid changes in aquifer head (or confined pressure) may not provide a valid, drawdown or recovery plot.

Slug tests can be performed on a well to establish its degree of hydraulic response, assuming that aquifer permeability is approximately known or can be estimated within an order-of-magnitude. Many of the references cited in this section describe how to conduct slug tests. The procedure is also described in Section 5.2 In-situ Hydraulic Conductivity Tests.

5.3-5.2 Pre-test Procedures

Before beginning the actual pumping test the following procedure should be followed to ensure getting the maximum amount of data from the test:

1. Install observation wells at appropriate locations. Geologic logs of the borings should be prepared to aid in the definition of aquifer conditions and interpretation of the pump test data.

2. Measure the water levels in the pumping well and the observation wells prior to the pump test. The period of pre-test monitoring should be equal to or longer than the anticipated duration of the pumping test. This pre-test monitoring will help to

identify the effects of barometric, tidal, or man-made influences on water levels. If nearby production wells are influencing water levels in the pumping or observation wells, it will be difficult to interpret the water-level response during the pump test. Consequently, prior to conducting a pumping test, efforts should be made to identify and eliminate controllable disturbances such as other pumping wells. It is recommended that water levels be monitored with a continuous water-level recorder, such as a float/chart recorder or a datalogger and transducer. See Section 5.1 Water-level Measurements for more information on the types of water-level measuring devices available.

3. Perform a short-term or step-drawdown test to determine the optimum pumping rate to be used during the test. Guidelines and procedures for conducting a step-drawdown test are outlined in subsection 5.3-6.

4. Set the pump discharge at the desired pumping rate. Shut off the pump and allow the water level in the pumping well to return to static conditions. Adjust the equipment to appropriate rates prior to the start of the test to minimize the amount of irregularity in the flow rate occurring in the early part of the actual test. Failure to stabilize the flow at the long-term pumping rate during the first 30 seconds to 2 minutes may jeopardize data analysis.

5.3-5.3 Test Procedures for a Constant-Rate Pumping Test

The following procedure should be followed to ensure consistency when conducting the actual pumping test:

1. Record meteorological data, particularly noting rainfall before, during, and after the test.

2. Just prior to the start of the pumping test, measure the static water levels in the pumping well and observation wells.

3. Synchronize watches.

4. Start the pump and, if adjustments are necessary, stabilize the flow rate as rapidly as possible.

5. Measure water levels in the pumping well and nearby observation wells at decreasingly frequent intervals. Table 5.3-1 presents recommended minimum time intervals for measuring water levels during a constant-rate pumping test. At least 10 measurements should be obtained over each log cycle; during the first minute, measurement frequency requires an automated technique. (It is also desirable to collect automated readings during the first-few hours of a test.)

For wells where measurements are made manually, a reasonable attempt should be made to adhere to the Table 5.3-1 schedule. In cases where electronic instruments are used to store digital readings, the frequency of measurement may significantly exceed this schedule during some log cycles.

6. During the pumping test, frequently monitor the pump discharge to make certain that a constant discharge is maintained. Adjust the discharge pipe valve as necessary.

7. Record field-measured water levels on appropriate forms. Examples of aquifer test forms are presented in Figures 5.3-10 and 5.3-11. If automatic recording instruments are used, manual measurements should be collected periodically to check the instrument data. Information about each well should also be recorded on the same sheet. Important data to be recorded in a field book or on the above-referenced forms are listed below:

   - Description of measuring equipment
   - Well diameter (ID)
   - Screened interval (MSL)
   - Nature of soil or rock around screen
   - Radial distance from the pumping well
   - Static water-level prior to pumping
   - Comments on activities or events that might affect the pumping test
   - Presence of a second fluid phase

8. Plot the drawdown versus elapsed-time data. Generally, semi-log plots are prepared but arithmetic plots are sometimes appropriate. If type-curve matching is necessary, log-log plots also should be prepared. Plotting the drawdown data during the test allows frequent re-evaluation of test duration for needed extensions, preliminary estimates of aquifer transmissivity and storativity, as well as early identification of aquifer boundaries, malfunctioning equipment, or improper data collection procedures. Field analysis of trends and slope changes on data plots will indicate when adequate data have been collected and the test can be terminated.

9. Turn off the pump.

10. Measure all water levels during well recovery. Ideally, water levels during recovery should be measured at the same time intervals as during drawdown. Recovery measurements should be collected until water levels stabilize or attain a 98 percent return to pre-test levels or for the duration of the withdrawal test whichever is less.

5.3-6 STEP-DRAWDOWN OR VARIABLE RATE TEST

A step-drawdown test is similar to a constant-rate test except that the pumping rate is systematically increased in a series of several steps of equal duration. The basic requirements of the constant-discharge test should be maintained for each step, including maintaining a constant pumping rate during each step of the test, and obtaining frequent water-level measurements in the pumping well and observation wells.

Generally, step-drawdown tests are conducted during a single day with each pumping step consisting of a 1-hour to 2-hour period. Consistent time intervals permit easy comparison of the drawdown data. It is desirable, but not critical, that the water level in the pumping well be allowed to recover to its static condition before starting the next discharge step of the test.

Step-drawdown tests are used to determine the specific capacity of a pumping well, optimum pumping rates, and the percentage of turbulent and laminar flow occurring at a pumping well. Under ideal, laminar-flow conditions, the drawdown in a pumping well is directly proportional to the discharge (Driscoll, 1986). If the flow is not entirely laminar, meaning that some turbulent flow also occurs, the drawdown will be proportional to the discharge rate raised to some power. Analytical equations have been developed to estimate the percentage of laminar versus turbulent flow from pumping wells (Driscoll, 1986). From such analyses a long-term test discharge rate can be selected that will avoid excessive turbulent flow.

5.3-7 DATA ANALYSIS

There are numerous methods available to evaluate pumping test data that utilize analytical equations, graphical techniques, numerical techniques, and/or computer-assisted techniques. These methods all depend on several different, but simplifying, assumptions. The art and skill in analyzing pumping tests requires the application of the appropriate analytical techniques to the specific aquifer and test conditions. Unfortunately, the analytical solutions of many drawdown and recovery tests are not unique. Correct evaluation requires a good understanding not only of the test response, but also of the geology in the test area and the hydrologic boundaries and anomalies.

When reviewing pumping test data, it is important to evaluate the simplifying assumptions of the method being applied to assure that it fits the aquifer and test conditions. Incorrect application of analytical methods can produce apparently realistic values of transmissivity and storativity, but may not provide reliable estimates of long-term aquifer response to pumping. At some sites, aquifer properties, such as transmissivity, can vary by as much as a factor of 10 from one location to another. Commonly, transmissivity, as determined from observation well data, will vary by a factor of 2 to 3.

Due to the large number and complexity of the various methods for analyzing pumping test data, only a few will be presented here for illustrative purposes. Table 5.3-2 is a compilation of some commonly used methods to analyze aquifer pumping test data, along with the basic assumptions inherent in each method and the source. Readers should refer to the sources directly in order to correctly apply the appropriate method. An excellent reference on this subject has been written by Kruseman and DeRidder (1983). The basic assumptions that should be determined and a description of analytical methods are discussed briefly below.

5.3-7.1 Basic Assumptions

Prior to selecting a specific method for analyzing the data, the following basic test conditions should be identified:

- Aquifer type (confined, unconfined, or leaky).
- Aquifer conditions (homogeneity, degree of isotropy, limits of areal extent, and natural flow gradient).
- Well characteristics (screen fully or partially penetrating the aquifer; possibility of wellbore or casing storage effects).
- Test type (constant-rate or step-drawdown).
- Test termination status of aquifer conditions (steady-state, non-steady-state).
- Boundaries (type and location).
- Seasonal trend effects.
- Weather effects (prior to test, during pumping, during recovery).

Once these variables have been described, an appropriate method can be selected for analyzing the pumping test data.

5.3-7.2 Analysis of Pumping Test Data

Analysis of pumping test data usually incorporates graphical data plots of time versus drawdown or distance versus drawdown and the application of analytical equations. There are basically two general types of methods used to evaluate well data: (1) type-curve matching methods, and (2) analytical solutions based on best linear fits derived from data plots. If possible, more than one specific method should be used to calculate aquifer parameters. If the aquifer and test conditions meet the applicability requirements of more than one method, alternative methods should produce reasonably close values of transmissivity and storativity.

In some cases, drawdowns may need to be corrected for various well effects such as partial penetration, barometric change, antecedent trends, aquifer dewatering, etc. References such as Todd (1980), Walton (1988), Stallman (1971), or Kruseman and DeRidder (1983) should be consulted.

5.3-7.2.1 Type-Curve Matching

Type-curves have been developed for a number of aquifer conditions, including confined, unconfined and leaky aquifers, delayed-yield effects for unconfined aquifers, steady-state and non-steady-state conditions, and effects of partial penetration. Pumping test data can be plotted and compared to a variety of type-curves in order to assess the conditions prevailing during the test. Although the type-curve method is somewhat subjective, it does allow for evaluation of complex aquifer responses that is not possible with simple analytical methods. A number of investigators have published type-curve matching methods, the most often referenced being Theis (1935), Hantush (1964), Cooper-Jacob (1946), Boulton (1954), Neuman (1975) and Neuman et al. (1984) (see Table 5.3-2).

Several computerized methods of curve matching are available for use when analyzing pumping test data, but the programs must be used with extreme caution because analysis of an aquifer test is not unique. Various combinations of aquifer conditions can yield the same drawdown response during a given test. Leaky aquifer effects may appear very similar to recharge boundary conditions. Consequently, a large amount of hydrologic judgment must be used when interpreting the fit, or match, of aquifer type curves to field drawdown data. Depending on the sophistication of the computer program and the user, the program may simplify or normalize the data so that important subtle response characteristics are obscured. Therefore, it is best to use carefully prepared plots of the test data and first perform the matching exercise manually in order to evaluate the various combination of aquifer conditions that might occur to produce a particular plot.

The general procedure for type-curve matching is described below:

1. The drawdown versus time data are plotted on a standard 3x5 cycle log-log graph.

2. The plot is overlain on the appropriate type-curve and a match-point is determined.
3. The match-point coordinates are taken from the plot and used in the calculation of the aquifer parameters.

Two examples of a type-curve matching method are presented in the Appendices. Figure A-1 illustrates the matching technique and solved equations for transmissivity and storativity for a Theis aquifer condition. A common aquifer condition of leakage through an aquitard that has negligible storativity is illustrated by a field example from Walton (1962) in Figure B-1.

5.3-7.2.2 Analytical Solution

Methods using analytical solutions consist of plotting the test data on semi-log or log-log graph paper and determining the slope of the plot or some other parameter, such as the y-intercept. This value is then used in the appropriate equation to calculate the aquifer parameters. These methods are less subjective than the type-curve method, but cannot be used if the data are affected by delayed yield or non-steady, leaky conditions. The most commonly used analytical solution is the Jacob Straight-line method, which is presented in Appendix C. An example of the application of the Jacob solution, showing solved equations for transmissivity and storativity, appears in Figure C-1.

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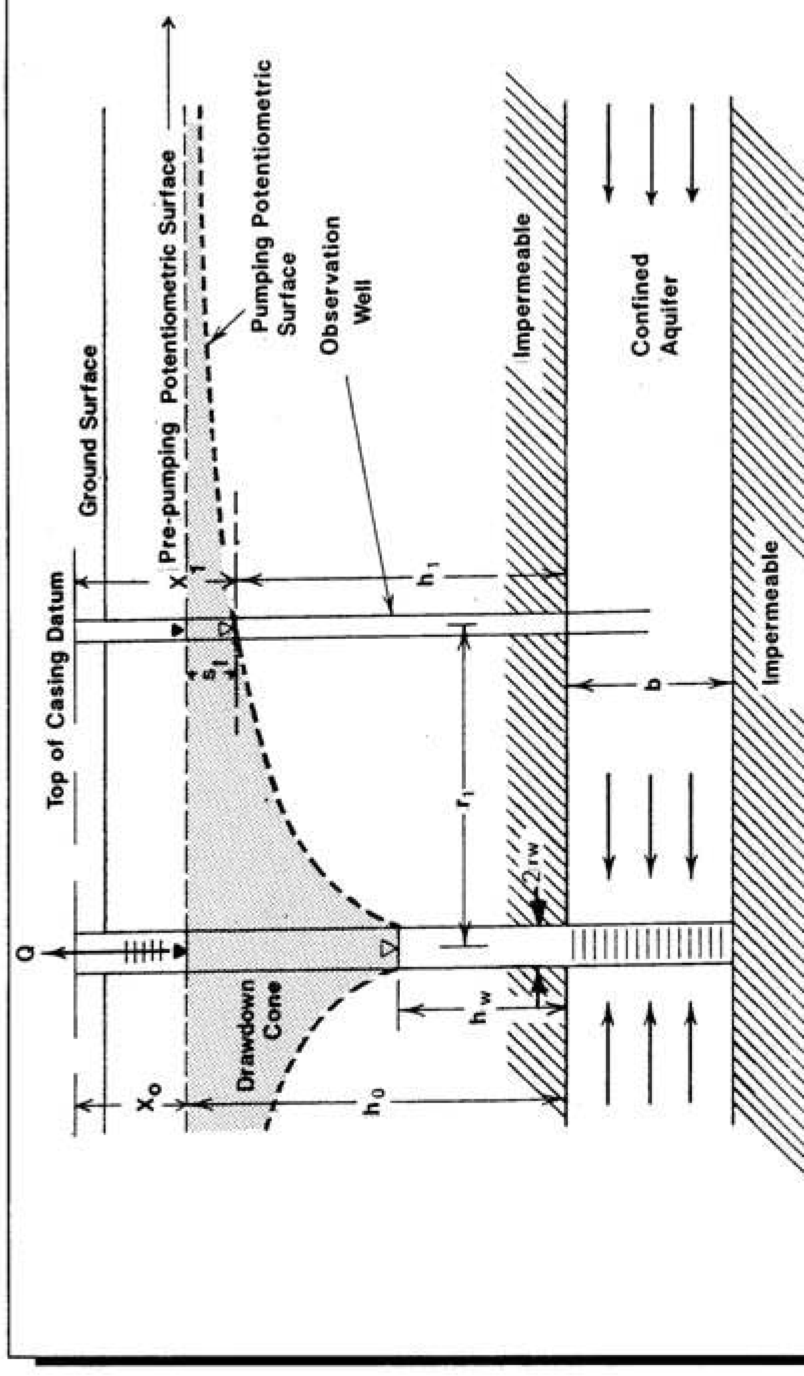


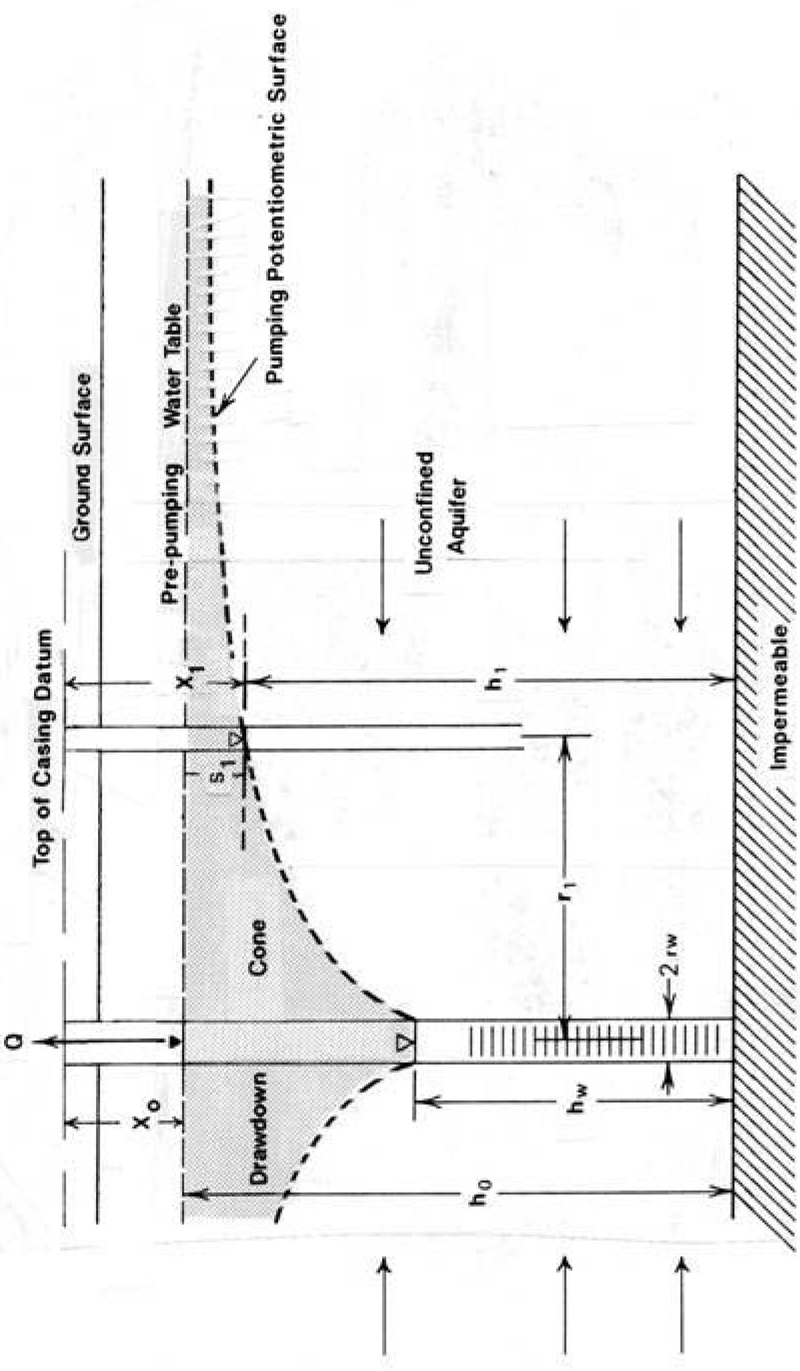
Source: After Todd (1980)

Symbol Definitions

- b = Aquifer Thickness
- h_o = Aquifer Head Above Datum
- h_1 = Head of Aquifer Above Datum at Observation Well
- h_w = Head in Pumped Well Above Datum
- Q = Discharge Rate of Well
- r_w = Radius of Pumped Well
- r_1 = Radial Distance Between Pumped Well and Observation Well
- s_1 = Drawdown at Observation Well
- X_1 = Measured Distance to Water-level in Observation Well
- X_o = Measured Distance to Static Water-level

Figure 5.3-1

Schematic Section of a Confined Aquifer Subjected to Pumping.



Note: See Fig. 5.3-1 for Symbol Definitions

Source: After Todd (1980)

Figure 5.3-2

Schematic Section of an Unconfined Aquifer Subjected to Pumping.

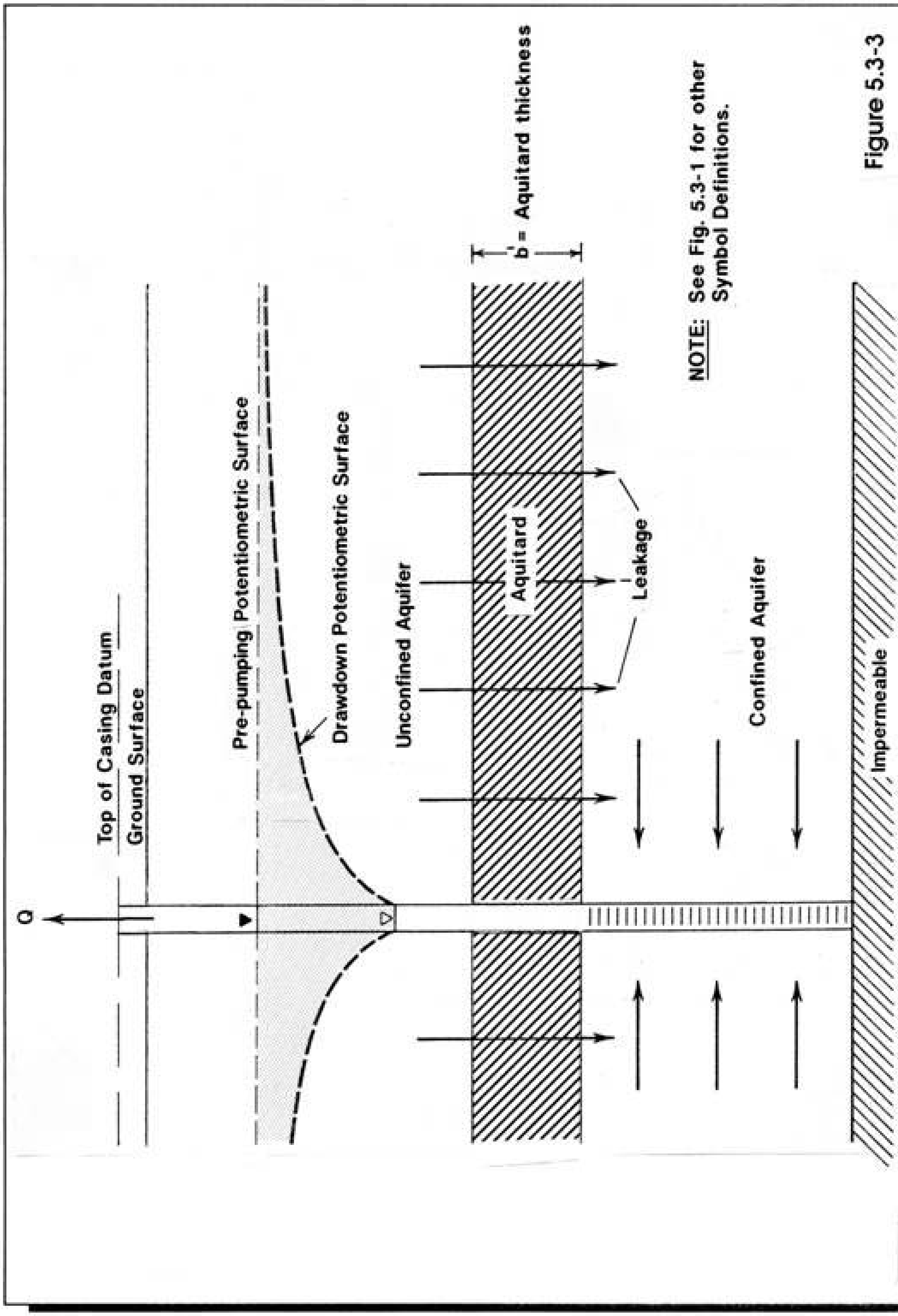


Figure 5.3-3

Schematic Section of a Leaky Aquifer Subjected to Pumping.

Source: After Todd (1980)

b = Total Aquifer Thickness
h_1 = Potentiometer Level in Upgradient Well
h_2 = Potentiometer Level in Downgradient Well
K = Hydraulic Conductivity of Aquifer
ΔL = Distance Between Upgradient and Downgradient Wells
T = Transmissivity of Aquifer

$$\frac{dh}{dL} = \text{Hydraulic Gradient} = \frac{h_1 - h_2}{\Delta L}$$

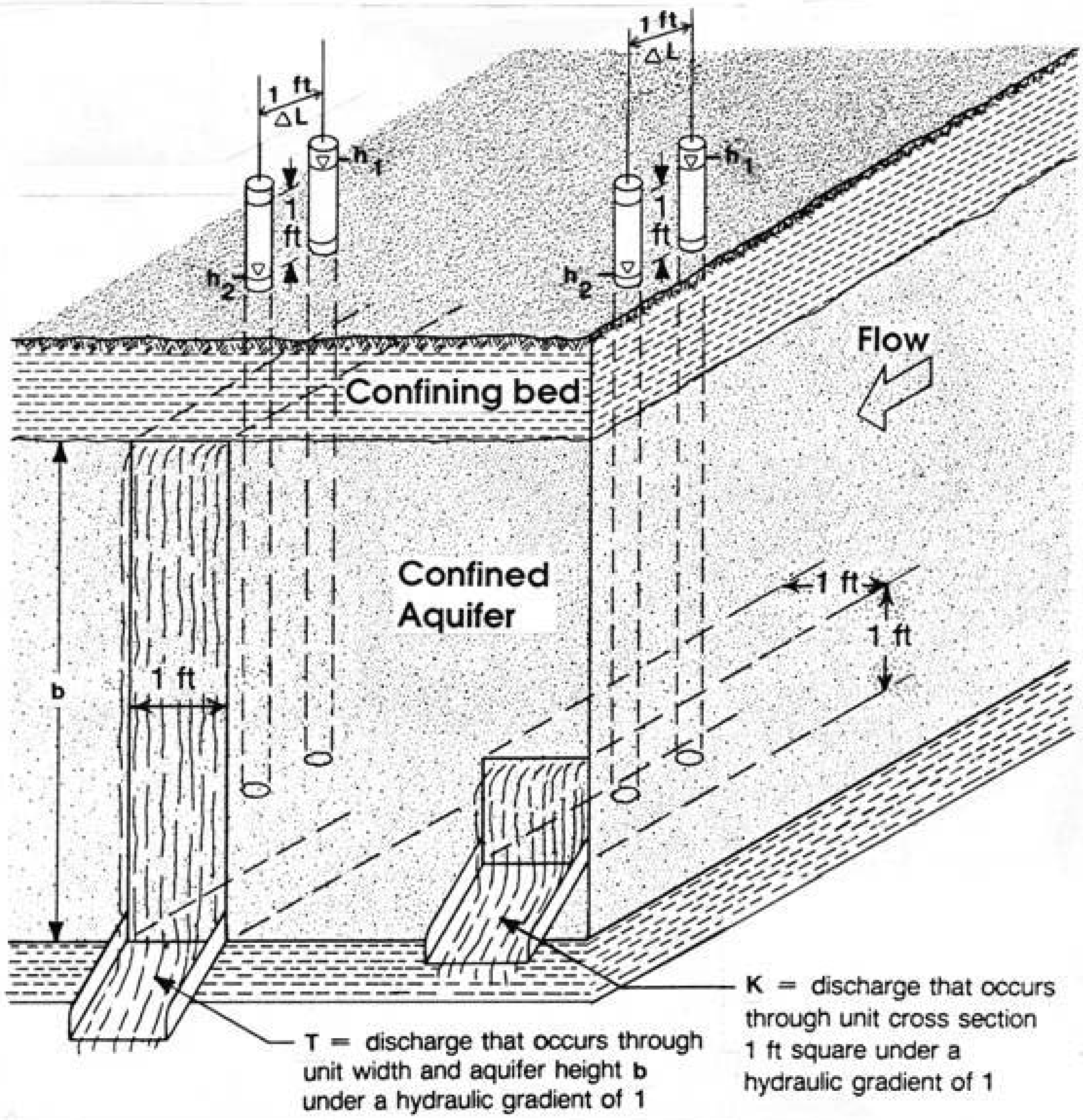
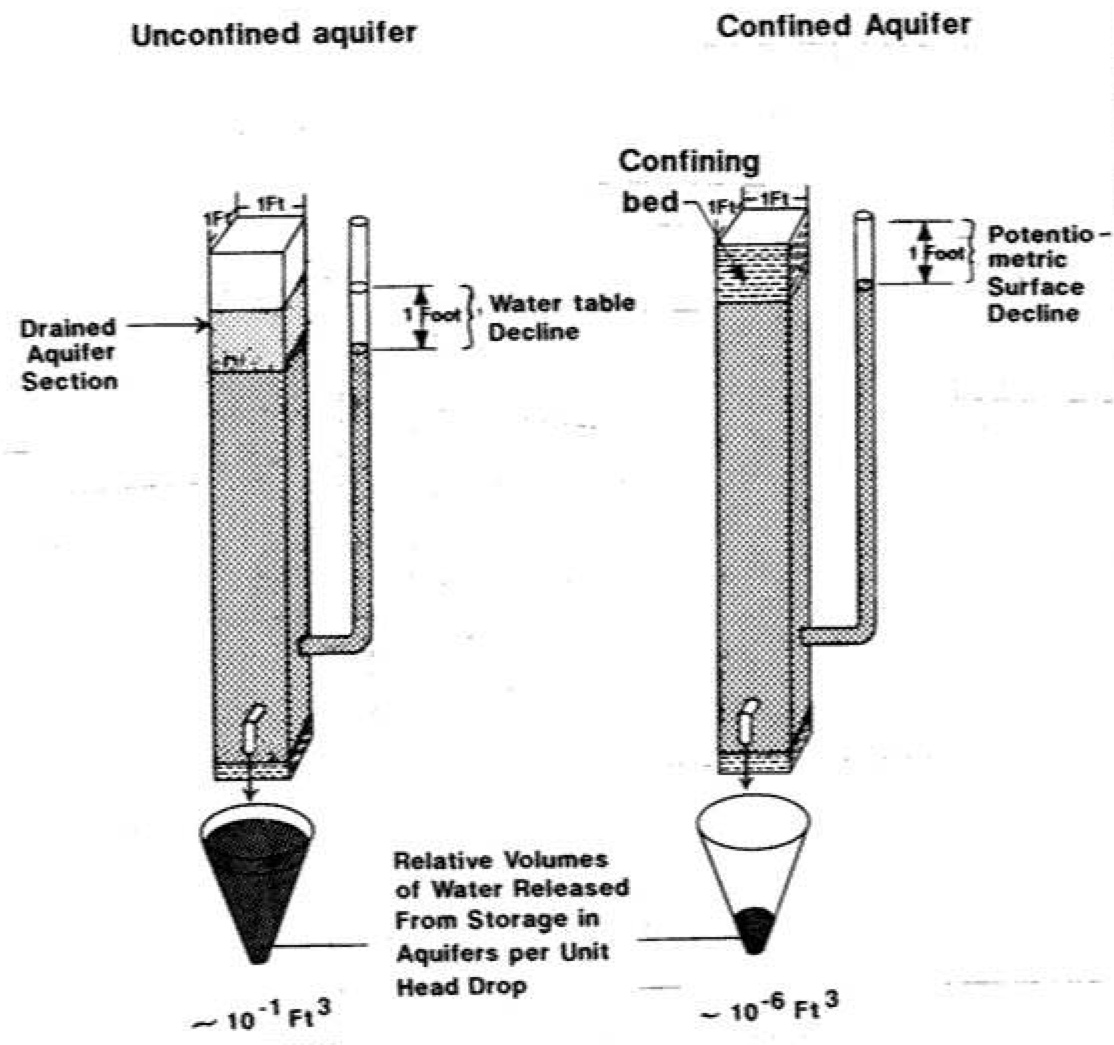


Figure 5.3-4

Source: After Driscoll (1986)

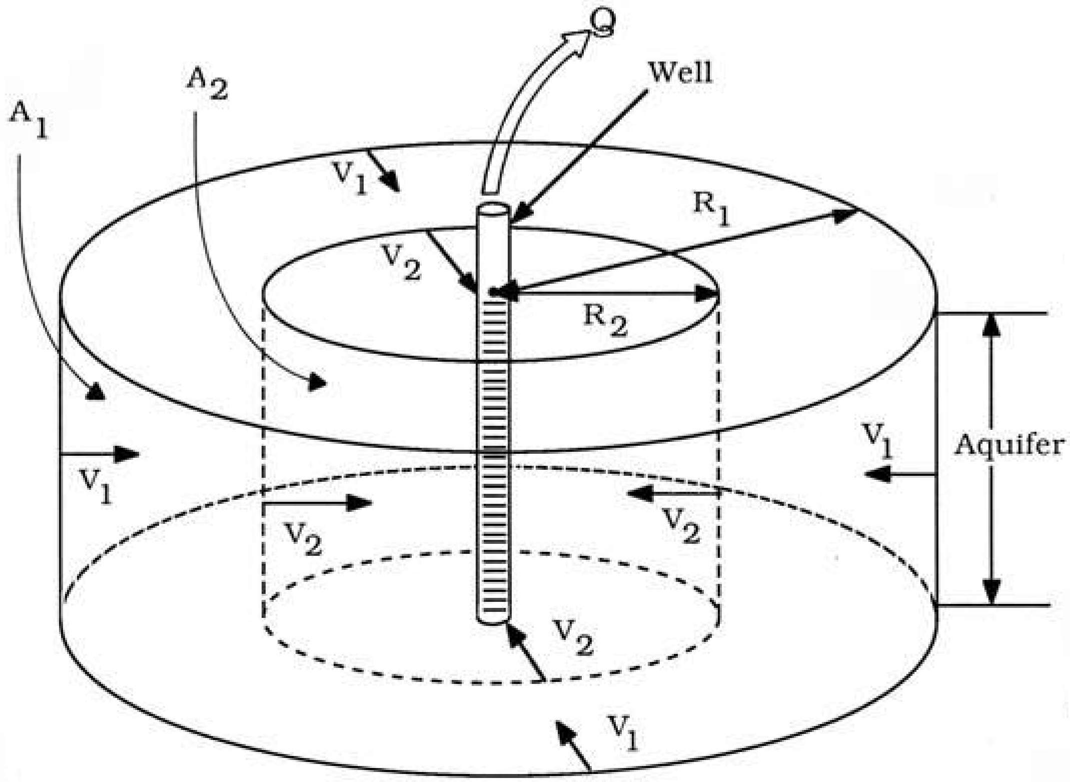
Conceptual Representation of Transmissivity and Hydraulic Conductivity for a Confined Aquifer.



Source: After Driscoll (1986)

Figure 5.3-5

Conceptual Representation of Storativity in Unconfined and Confined Aquifers.

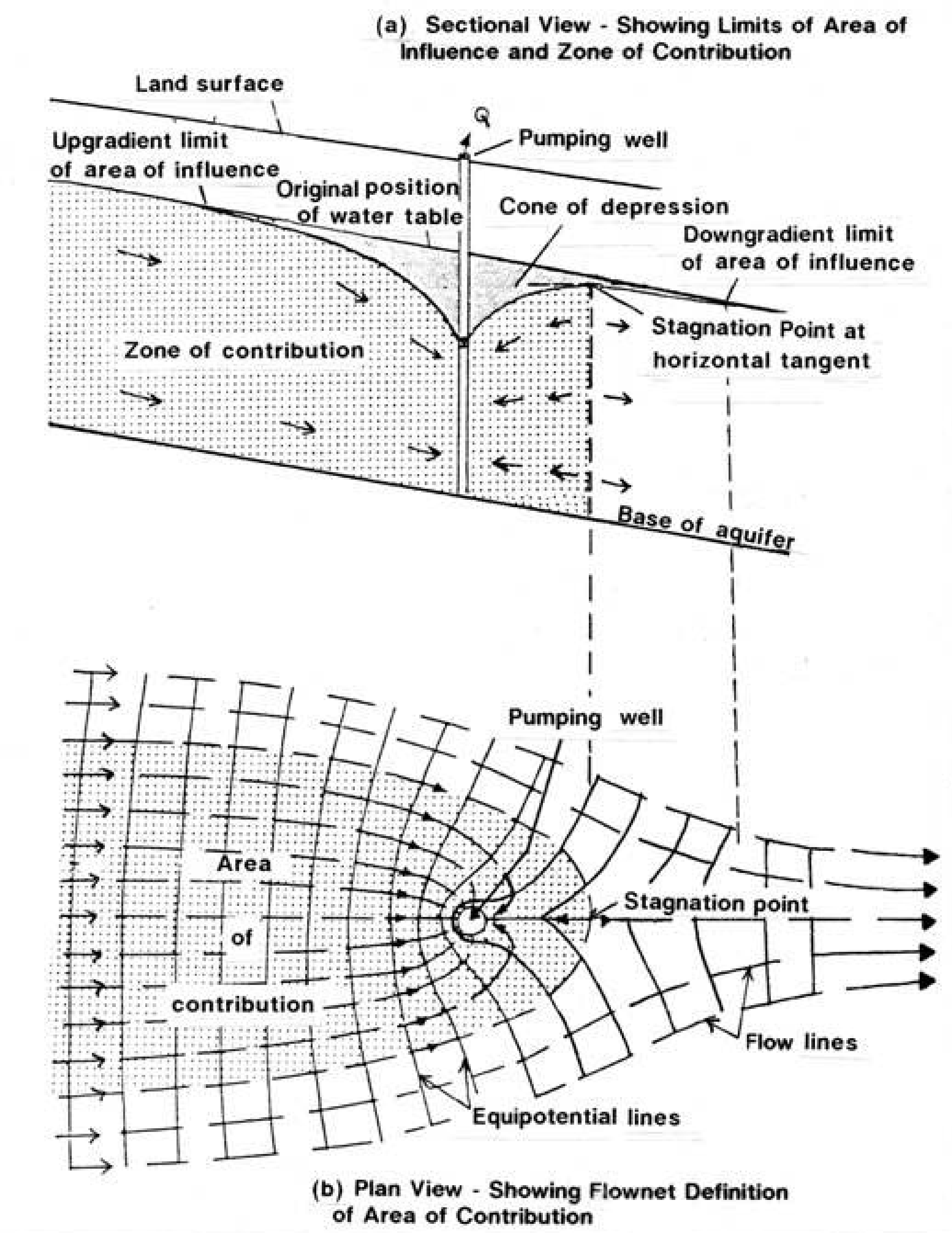


Note: Per Title Conditions, all V_Is are Identical

	Radius (R)		Cylinder Area (A)		Ground Water Velocity (V)
If,	$R_1 = 2R_2$	**then,**	$A_1 = 2A_2$	**and,**	$V_2 = 2V_1$

Figure 5.3-6

Convergent Uniform Radial Flow in a Homogeneous, Isotropic Aquifer Due to Pumping of a Fully Penetrating Well.

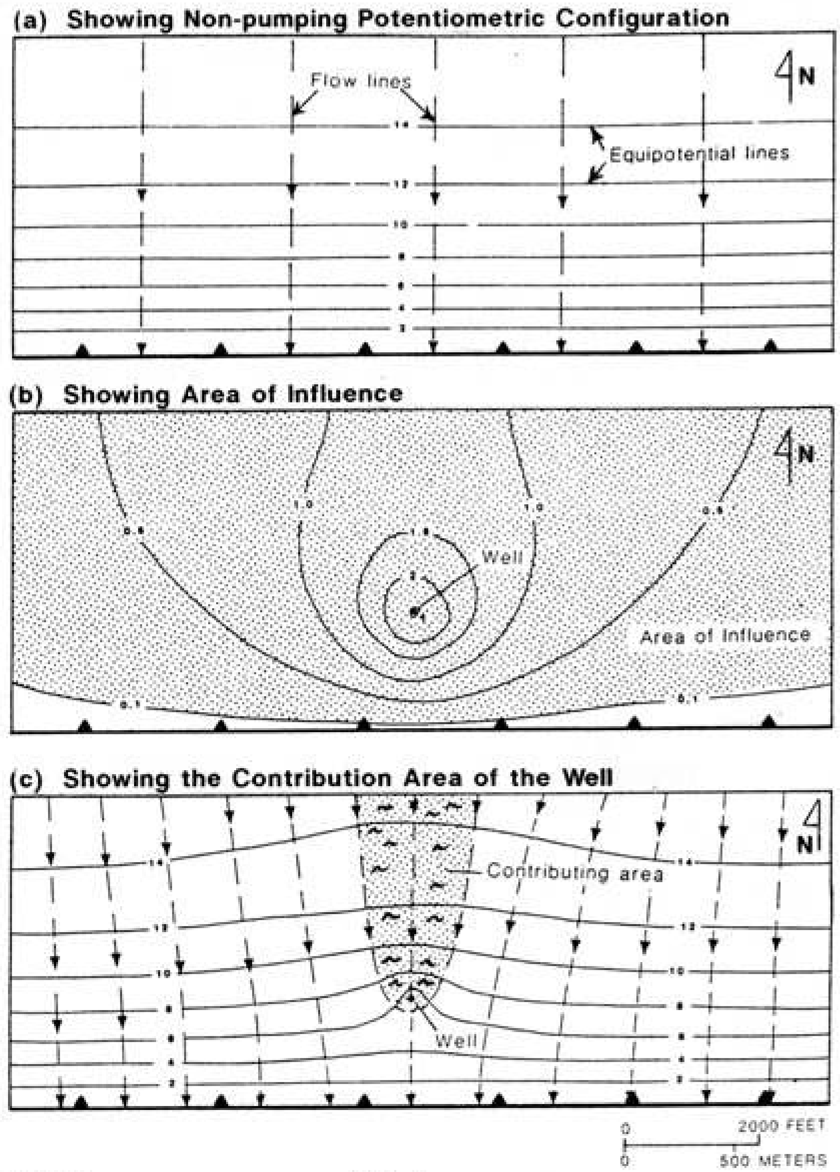


Note: Under this development of the cone of depression, groundwater downgradient of the stagnation point will not be drawn to the well and discharged

Source: After Morrissey (1987)

Figure 5.3-7

Diagram of Groundwater Flow Around a Pumping Well.



AREA OF INFLUENCE

CONTRIBUTING AREA

LINE OF EQUAL WATER LEVEL, OR DECLINE
Interval, in feet, is variable.

DIRECTION OF GROUND-WATER FLOW

CONSTANT- HEAD RIVER BOUNDARY (OTHER BOUNDARIES ARE ZERO INFLOW)

Note: FOR ALL FIGURES, UNITS OF HEAD AND DRAWDOWN EXPRESSED IN FEET RELATIVE TO RIVER STAGE

Figure 5.3-8

Source: After Morrissey (1987)

Flow Diagrams for a Hypothetical Aquifer for Steady-state Pumping.

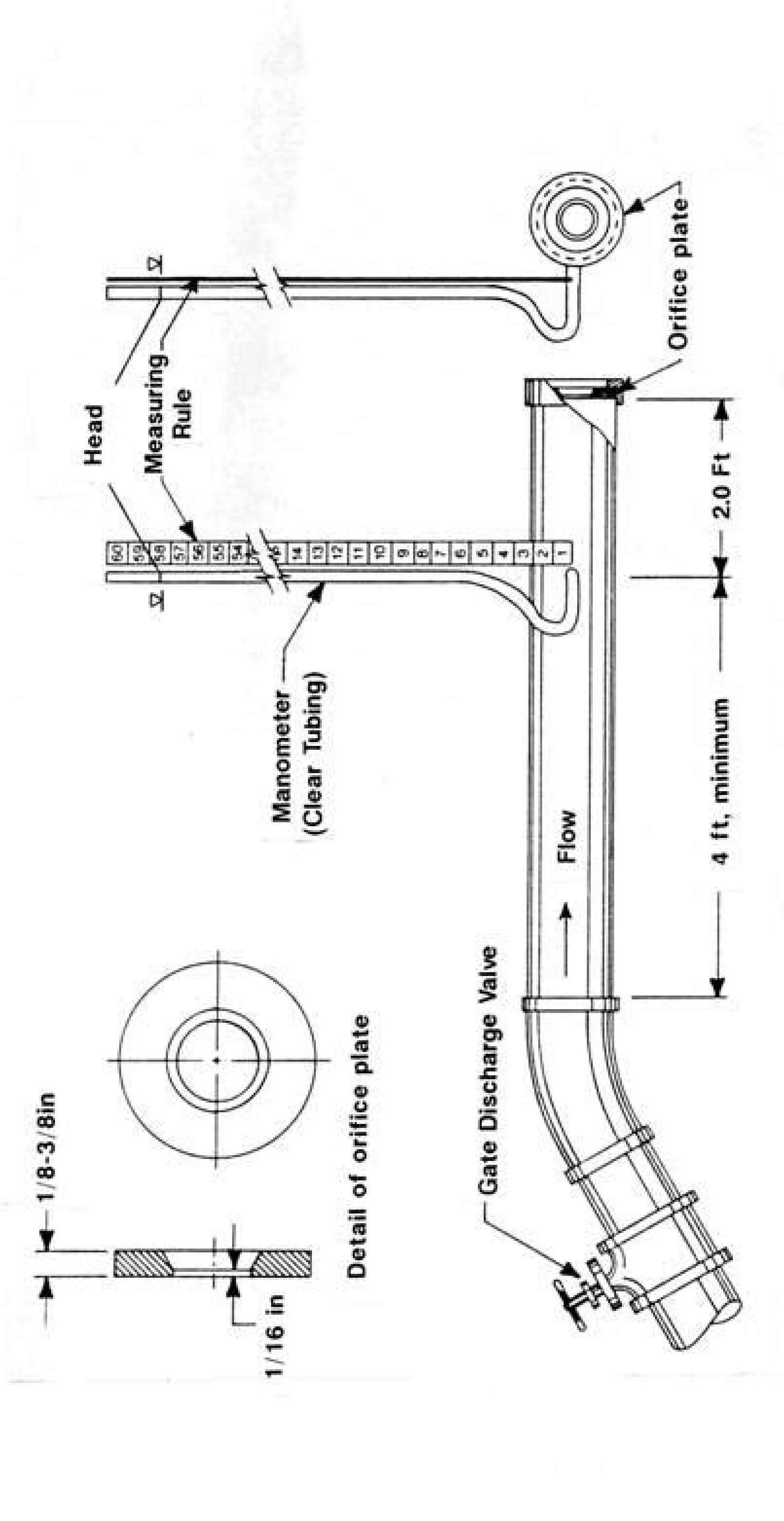


Figure 5.3-9

Diagram Illustrating the Circular Orifice Weir Method for Measurment of Well Discharge.

Source: After Driscoll (1986)

CONSTANT-RATE PUMPING TEST DATA

Date ________________ Site ________________________________ Well ________________________

Radial Distance from Pump (r) __________(ft) Screened Depth ______________ Static WL (x_o) ______________

Measuring Point Used ____

Elapsed Time (t) (min)	Distance to WL (x) (ft)	Drawdown $(x-x_o)$ (ft)	Barometric Reading (inches-Hg)	Corrections to Drawdown (ft)	Drawdown Corrected (s) (ft)	$\frac{t}{r^2}$ $\frac{min}{ft^2}$	Pumping Rate (gal/min) and Remarks

See Figures 5.3-1 for Symbol Definitions

Source: ABB-ES

Figure 5.3-10

Example of an Aquifer Test Data Form for Recording Water-level Drawdown.

PUMPING TEST RECOVERY DATA

Date ________________ Site ____ Well ________________________

Radial Distance from Pump (r) __________ (ft) Screened Depth ______________________ Static WL (x_o) ______________

Measuring Point Used ____

Elapsed Time (t) (min)	Time Since Pump Off (t') (min)	t/t'	Distance to WL (x) (ft)	Residual Drawdown ($x-x_o$) (ft)	Barometric Reading (inches-Hg)	Corrections to Residual Drawdown (ft)	Residual Drawdown Corrected (s') (ft)	Remarks

See Figures 5.3-1 for Symbol Definitions

Source: ABB-ES

Figure 5.3-11

Example of an Aquifer Test Data Form for Recording Water-level Recovery.

Time After Pumping Started (minutes)	Measurement Frequency
0-1.5	15 seconds
1.5-5	30 seconds
5-15	1 minute
15-50	5 minutes
50-120	10 minutes
120-240	20 minutes
240-500	40 minutes
500-1000	1 hour
>1000	4 hours

Note: More frequent measurements at the start of the test is desirable

Source: Adapted from Walton (1987)

Table 5.3-1

Minimum Recommended Time Intervals for Measuring Water Levels During a Constant-rate Pumping Test

General Flow Conditions*	Method Name (citation)	Inherent Assumptions**	No. of Monitored Wells Required	Parameters Determined **	Solution Technique	Data Plot
UNE, CNE	Theis (1935)	a-f, h	1/(2 or more)	T, S, boundaries	curve-match	log-log s vs, t (or s vs. t/r^2)
USS, UNE, CSS, CNE	Cooper-Jacob (1946)	a-h	1/(2 or more)	T,S, boundaries	analytical	semi-log s vs. t (or s vs. r)
CSS	Thiem (1906)	a-c,e	2 or more	T	anlaytical	semi-log s vs. r
USS	Thiem (1906)-Dupuit	a-c,e,h-j	2 or more	T	anlaytical	semi-log s vs. r
UNE	Boulton (1954)	a-d,h,m	1	T,S,K'	curve-match	log-log s vs. t
UNE	Papadopulous (1967)	a-c,e,f,h	1(pumped)	T,S ?	curve-match	log-log s vs. t
UNE, CNE	Theis Recovery (1935)	a-h	1	T,S, boundaries	anlaytical	semi-log s vs. t/t'
UNE, CNE	Weeks (1969)	a,b,d,h,k-m,p	3 or more	$T,K_r/K_z S$	curve-match	semi-log s vs. t
UNE	Streltsova (1974)	a,b,d,h,k-m,p	2	T,S	curve-match	log-log s vs. t
UNE	Boulton and Streltsova (1976)	a,b,h,k-m,p	2	T,S	curve-match	log-log s vs. t
SSS, SNE	Hantush and Jacob (1955), Walton (1962)	a-e,k,n,p	2 or more	T,S,K'/b'	curve-match	log-log s vs. t
SNE	Hantush (1964)	a-e,p	1 or more	T,S,K',S'	curve-match	log-log s vs. t/r^2
SNE	Witherspoon et al (1967)	a-d,k,p	2	K'/S'	curve-match	log-log s vs. t @ equal r
SNE, CNE	Way and McKee (1982)	a-d,k,p	3 obs	$K_xK_yK_zS$	curve-match	log-log s vs. t
CNE	Neuman et al (1984)	a-d,f,p	3 or more	K_xK_yS	analytical	semi-log s vs. t
CNE	Hantush (1961)	a,b,d-f,p	1	K,S	curve-match	log-log s vs. t
UNE	Neuman (1975)	a-d,h,m	1	T,S, K_z/K_r	curve-match	log-log s vs. t

* Codes: USS = unconfined steady-state, UNE = unconfined non-equilibrium, SSS = semi-confined steady-state, SNE = semi-confined non-equlibrium, CSS = confined steady-state, CNE = confined non-equilibrium

** See explanation of symbols on Page 2 of 2.

Notes: The references cited are included in the references or additional references of section 5.3

Source: MADEP, After Stallman (1971)

Table 5.3-2
Page 1 of 2
Commonly-used Methods for Analyzing Aquifer Pumping Test Data (Porous Media)

Explanation of Symbols

Assumptions

a = constant pumping rate
b = homogeneous, infinite aquifer
c = pumping and/or observation wells screened full aquifer thickness
d = pumping well has and infinitesimal diameter (neglectable well storage)
e = aquifer is isotropic
f = no delayed drainage, or vertical leakage into or out of aquifer
g = u <0.01 to 0.1
h = drawdown (or recovery) is corrected for changing saturated thickness unless drawdown is small in comparison to initial saturated thickness
i = potentiometric surface is horizontal prior to pumping
j = flow in aquifer is horizontal
k = observation well is partially penetrating
l = $r < 1.56 (K_h/K_z)1/2$
m = principal; permeabilities are oriented parallel to coordinate axis
n = leakance is proportional to head variation
p = other limiting conditions

Parameters

b' = thickness of aquitard
K = hydraulic conductivity of aquifer (horizontal)
Kr = radial hydraulic conductivity
Kv = vertical hydraulic conductivity
Kx = hydraulic conductivity x-coordinate direction
Ky = hydraulic conductivity in y-coordinate direction
Kz = hydraulic conductivity in z-coordinate direction
K' = hydraulic conductivity of aquitard (vertical)
r = radial distance between pumped well and observation well
s = measured residual drawdown for a given r and t
s' = measured residual drawdown for a given r and t after pumping ceased
S = storativity (storage coefficient) of aquifer
S' = storativity (storage coefficient) of aquitard
t = total elapsed time since pumping began
t' = elapsed time since pumping ceased
T = transmissivity (transmissivity) of aquifer

Source: MADEP, after Stallman (1971)

Table 5.3-2
Page 2 of 2
Commonly-used Methods for Analyzing Aquifer Pumping Test Data (Porous Media)

APPENDICES

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APPENDIX A

Application of the Theis Curve-matching Method

The transmissivity (T) and storativity (S) of an aquifer can be determined by this method if the following conditions are satisfied, or if it is assumed that these conditions are not seriously violated.

- The aquifer is homogenous and isotropic
- The aquifer boundaries are beyond the edge of the drawdown cone of the pumping well during the entire test period
- The discharging well penetrates the full thickness of the aquifer
- The well diameter is not large enough to cause casing storage effects at the test discharge rate
- No vertical leakage of water occurs from aquitards either overlying or underlying the pumped aquifer

Using the type-curve matching procedure given in Section 5.3-7.2.1, aquifer transmissivity is calculated as:

$$T = \frac{114.6\,Q}{s}\,W(u)$$

where,

T = aquifer transmissivity (gpd/ft)

Q = average pumping rate in gallons per minute (gpm)

s = drawdown read from data plot corresponding to the selected match point (feet)

W(u) = the exponential integral called the well function of u, which is usually selected during type-curve matching to be a value of 1 on the Y-axis of the Theis-curve plot (dimensionless)

Aquifer storativity is calculated for each observation well plot (but not the pumped well) of either drawdown or recovery as:

$$S = \frac{T\,t\,u}{1.87\,r^2}$$

where,

S = aquifer storativity (dimensionless)

T = transmissivity calculated using the above equation (gpd/ft)

t = time read from data plot corresponding to the selected match point (converted to days)

r = radial distance from pumping well to observation well (feet)

u = the independent variable of the function W(u), which is usually s

If drawdown versus time data are available for two or more observation wells located at differing distances from the pumped well, the data should be plotted on the X-axis as t/r. This procedure removes the variable distance factor, and will cause drawdowns of all wells to lie along a single positioning of theTheis-curve, if the Theis conditions given above are satisfied.

Figure A-1 gives an example of the application of the Theis method with solved equations for transmissivity and storativity. In this case, a moderately fractured and weathered dolomite aquifer is confined by the overlying clayey residuum. Due to the thinness of the fractured zone (about 20 ft) and the relatively high aquifer storativity, drawdown did not reach the observation well at a distance of 300 feet until about 200 minutes pumping at 10 gpm. The wandering of data points along the Theis-curve (Figure A-1) is typical of tests conducted where the aquifer possesses a minor degree of geologic heterogeneity.

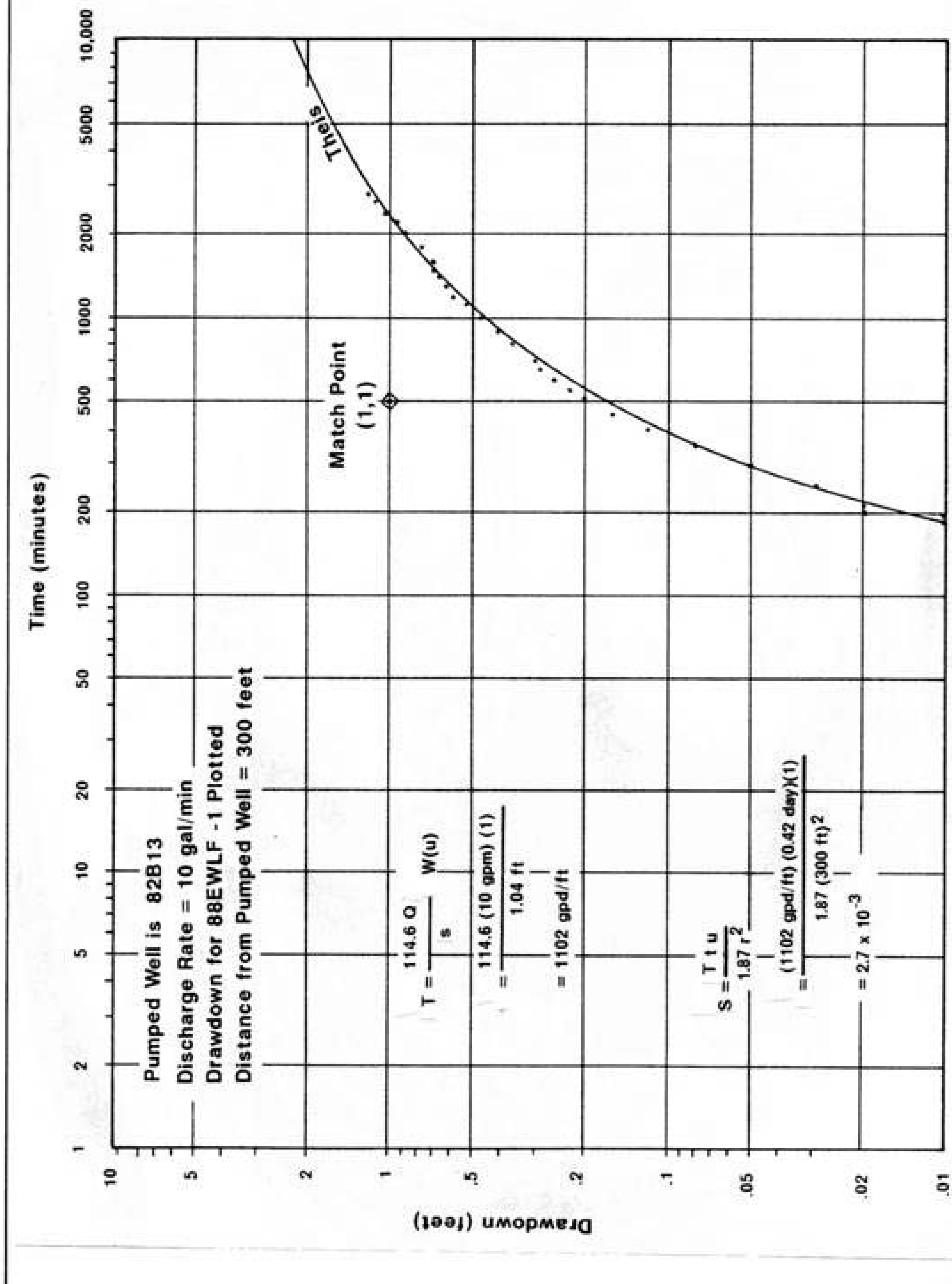

Figure A-1

Example Analysis of Pumping Test Data with Theis' Curve Method.

Source: ABB-ES

APPENDIX B

Application of Walton's Type-curves for a Leaky Semi-confined Aquifer without Storage in the Aquitard

One of the more common reasons that drawdown data do not plot along the Theis curve is that a significant quantity of water being pumped from a well comes from vertical leakage from adjacent aquitards. An aquitard is a geologic unit that immediately overlies or underlies an aquifer, and partially confines the aquifer. Aquitards possess a high enough vertical hydraulilc conductivity to allow leakage of water into the aquifer under hydraulic gradients.

Families of type-curves have been developed for two different leaking aquitard conditions: (a) leakage without water derived from aquitard storage, and (b) leakage of water derived exclusively from aquitard storage. Condition (a) generally occurs when the aquitard is relatively thin and/or relatively permeable, and is in contact with a second aquifer (called a source bed). Condition (b) occurs when the aquitard is relatively thick and has very low hydraulic conductivity compared to the pumped aquifer. The leakage-with-storage response may also appear on data plots of short duration pumping tests if actual geologic conditions are between (a) and (b). Lohman (1979) advised that "thorough knowledge of the geology, including the character of the confining beds, should indicate in advance which of the two leaky aquifer type-curves to use, or whether to use the Theis type-curve for non-leaky aquifers."

The analytical procedure to interpret drawdown measured at an observation well follows nearly the same data-plotting and curve-matching routine as for the Theis method. Data are prepared and plotted as discussed in Section 5.3-7.2.1. The field data plot is fitted to the most appropriate curve in the family of type-curves, and a match point corresponding to the type-curve coordinates of unity (if possible) is determined. The equations for calculating transmissivity and storativity are the same as those given in Appendix A (Theis method). W(u) and u essentially become leaky well function parameters, with the match point location on the data plot giving s and t values that reflect leakage.

The example shown in Figure B-1 is for leaky condition (a), where a 63-foot thick aquifer is overlain by a 20-foot thick aquitard that is, in turn, overlain by a second aquifer. It is assumed that recharge to the source bed maintains a constant head in this bed, balancing loss of water due to vertical leakage to the pumped aquifer.

The drawdown plot in Figure B-1 has been matched with a specific leakage curve (r/B = 0.2). All curves in this family of type curves go flat (no increase in drawdown with time) when the drawdown cone expands radially far enough so that the total rate of leakage equals the constant discharge rate of the well. This condition occurs at about 200 minutes in the example. The Theis-curve is shown in its appropriate position for the given match point to illustrate the increasing difference of drawdowns between a non-leaky and a leaky analysis with elapsed pumping time.

The vertical hydraulic conductivity (K') of the aquitard can be calculated in leaky aquifer analyses once the transmissivity and fitted type-curve are known. For leaky conditions with no aquitard storage, the equation for K' is:

$$K' = \frac{T\,b'}{B^2}$$

where,

K' = vertical hydraulic conductivity of aquitard (gpd/ft^2)
b' = aquitard thickness (feet)
B = leakage factor, derived by dividing the radial distance (r) by the numerical value of the matched curve (feet)
T = aquifer transmissivity (gpd/ft)

Figure B-1 shows this calculation for the above field example.

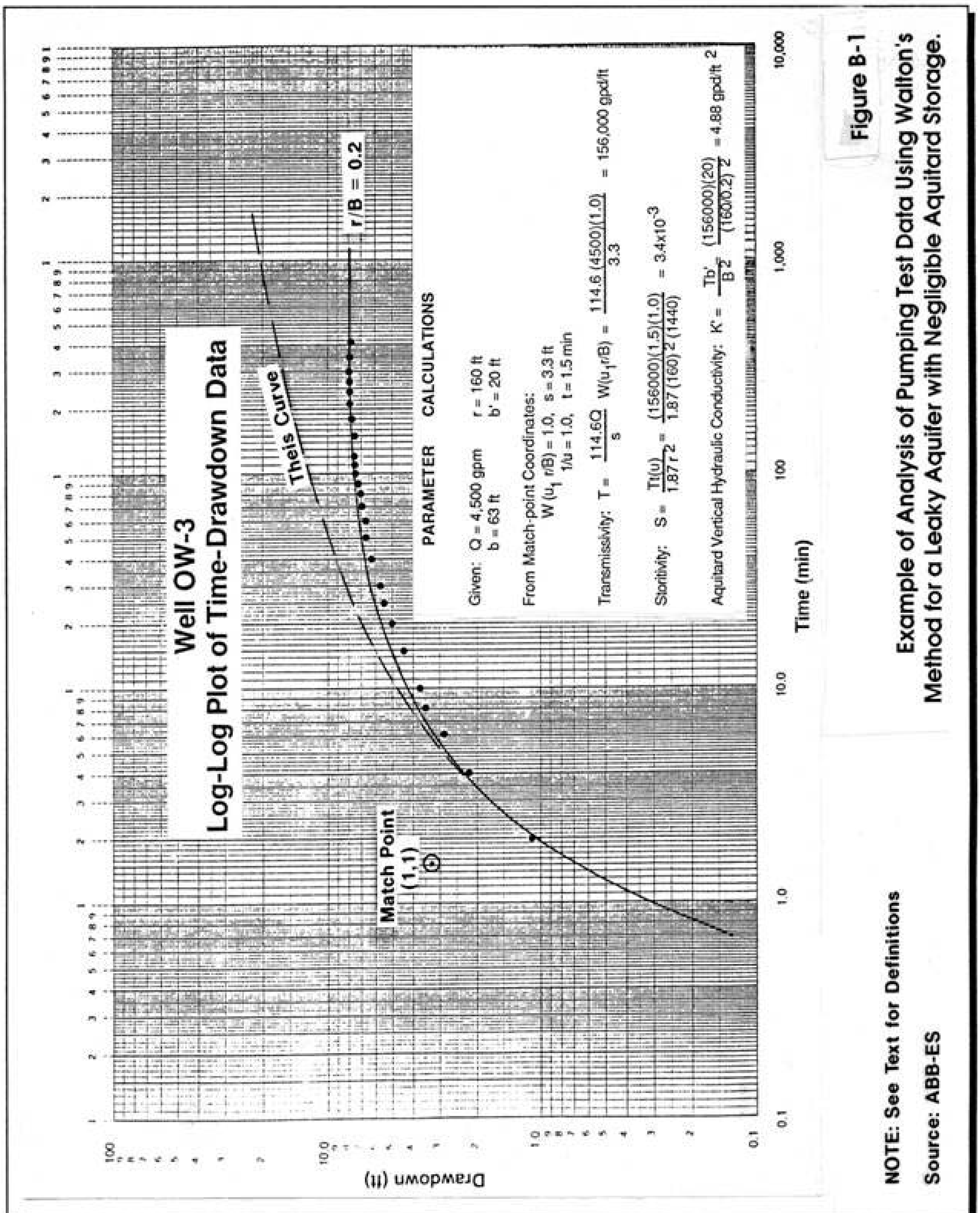

Figure B-1

Example of Analysis of Pumping Test Data Using Walton's Method for a Leaky Aquifer with Negligible Aquitard Storage.

APPENDIX C

Application of Jacob's Straight-line Method

Jacob's method is based on the modification of Theis' equation and is represented by the following equation:

$$s = \frac{264\ Q}{T} \log \frac{0.3T\ t}{r^2 S}$$

where,

- s = drawdown in the aquifer at a point corresponding to r and at time of t (feet)
- Q = test discharge rate (gallon per minute)
- T = aquifer transmissivity (gallon per day/foot)
- t = time since pumping began at rate Q (minutes)
- r = radial distance from observation well to pumping well (feet)
- S = aquifer storativity (dimensionless)

A plot of drawdown (s) versus time (t) on semi-logarithmic paper (with t on the logarithmic scale) should form a straight line having a slope Δ s/log t with an absolute value equal to 264 Q/T. When this line is extended until it intercepts the time-axis (i.e., where s = 0), the time interception point is termed t_o.

By constructing the best-fit straight line through the data points on the semi-logarithmic plot, the values of transmissivity (T) and storativity (S) may be computed as:

$$T = \frac{264\ Q}{\Delta s}$$

$$S = \frac{0.3T\ t_o}{r^2}$$

Where,

- Δs = drawdown over one log cycle along straight line (feet)
- t_o = time-axis intercept of straight line (minutes)

and, all other terms are as defined above.

Use of the Jacob method has been prolific among pumping test analysts because of its simplicity, general applicability to both confined and unconfined aquifers, and dependence on late-time test data rather than early time data, which normally are much more susceptible to inaccuracies in field procedures. However, this method must be used with caution as it is invalid for some of the commonly encountered physical constructions of aquifers and their flow conditions (Sen, 1988).

The basic underlying assumptions for use of the Jacob method are:

1) the well discharge (Q) is held at a constant rate throughout the test (a variance of 10 percent may jeopardize interpretation).

2) the pumped well is open to the full thickness of a homogeneous, isotropic, and uniformly thick aquifer.

3) well casing storage is negligible at the test discharge rate, or the initial time duration of affected drawdown or recovery data is so short that it does not cause inappropriate straight-line fitting.

4) discharge from the well (and recovery of the drawdown cone) is by water derived exclusively from storage in the aquifer (i.e., no vertical leakage from underlying or overlying aquitards).

Conditions under assumptions 1-3 are usually controllable by the investigator and should be readily testable. An equation to calculate the elapsed pumping time (t_c) when casing storage becomes negligible is:

$$t_c = \frac{0.6\,(d_c - d_p)}{Q/s}$$

where,

d_c = inside diameter of well casing (inches)

d_p = outside diameter of pump column pipe (inches)

Q/s = specific capacity of the well (gpm/ft of drawdown) at time t_c

The Jacob method will not give correct values for transmissivity and storativity if the plotted data that are fitted to a straight line are affected by the cone of depression encountering aquifer boundaries, either barrier or recharge types. Barrier boundaries will cause the slope of the plotted data to increase, while a recharge boundary (such as a river) will cause the slope to decrease. Vertical leakage will result in the data plot becoming convex for a variable period of time followed by another variable time span during which a nearly straight-line trend is likely.

If leakage is present, the initial straight-line plot segment usually will not conform to Jacob method requirements, and the later straight-line segment is always invalid.

A specific mathematical requirement for valid application of the straight-line method, cited by many authors, is that u (called a dimensionless time factor) be less than about 0.01 for the data points fitted to a straight line. Theis (1935) derived u as:

$$\mu = \frac{r^2 S}{1 - 4 t T}$$

where (in consistent English units),

r = radial distance of observation well from pumping well (feet)
S = aquifer storativity (dimensionless)
T = time (elapsed) of data point being tested (days)
T = aquifer transmissivity (feet squared per day)

In practice, it has been found that u may reach about 0.1 before this technique becomes invalid (Murray, 1987).

Sen (1988) points out that non-Darcian turbulent flow near the well will invalidate a Jacob analysis of drawdown data that follow a straight line on semi-log plots. In his article, Sen gives a rigorous data-manipulation procedure to check the validity of the Jacob method for any data set. Although the Sen test could be performed regularly, it is recommended that when any analysis is being performed on data collected in a geologic setting that potentially may deviate from the Jacob-method requirements, a log-log, type-curve analysis also be performed. Commonly, the two approaches complement and/or corraborate interpretations of one another.

An example of the Jacob straight-line method applied to pumping test recovery data is given in Figure C-1 (Appendix). Instead of simply plotting drawdown versus elapsed time as would be done for data collected during pumping, residual drawdown is plotted against total elapsed time since pumping began divided by elapsed time since pumping stopped (t/t'). Residual drawdown is the difference between the water-level elevation corresponding to any given t' and the pre-pumping static elevation.

In Figure C-1, recovery data were not collected long enough for the water level to return to the pre-pumping static level. However, the fitted straight-line is extended to zero residual drawdown where a value is read for t/t', and subsequently a t' value can be determined for use in Jacob's storativity equation.

Recovery analyses often give more reliable values of transmissivity and storativity than drawdown analyses. When pumping rates are low due to low permeability geologic materials typical of many contamination sites, the effect of variable discharge at low rates during a test is minimized by analyzing recovery data with the Jacob method. The average pumping rate for the entire period of pumping must be used in Jacob's equation for transmissivity.

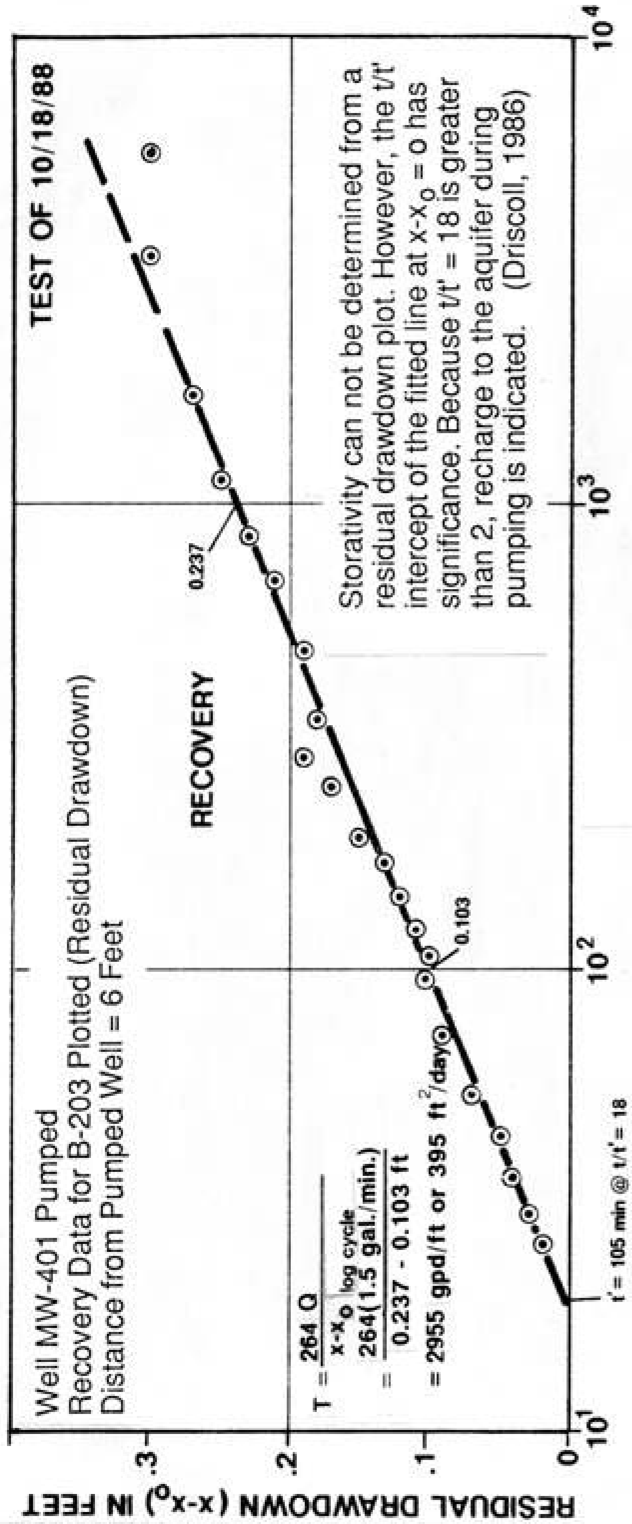

Figure C-1

Example of Jacob's Straight-line Analytical Solution.

Source: ABB-ES

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 5.4 PACKER TESTS

SECTION 5.4 PACKER TESTS

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5.4 PACKER TESTS

5.4-1 PURPOSE

Water pressure tests or "packer tests" are in-situ tests performed to measure the permeability of a specific zone in a bedrock borehole. Water pressure tests are used to estimate bedrock permeabilities for hydrogeologic studies and in estimating grouting and dewatering requirements for construction purposes.

Packer tests may be done during the advancement of the borehole or after drilling is completed. Packer tests are usually conducted in NQ/NX-size (3-inch) boreholes, but can be conducted in boreholes of a larger size. The test involves placing expandable packers, either mechanical or pneumatic, in a borehole. A pneumatic packer assembly is preferred because it is easier to use and provides a more positive seal. A section of the borehole, usually five feet in length, is sealed off with the packers. Water is then pumped through the zone between the packers at a known pressure. The rate of flow into the formation is measured with a flow meter. The permeability of the test zone is calculated using the data obtained in the test.

5.4-2 METHODOLOGY

The following methodology was designed to present the general requirements of a bedrock packer test. It is advisable to consult additional references before actually performing this type of test.

1. Flush the borehole with clean water to remove cuttings. Measure the depth of the borehole, and check for caving. Be sure that an adequate reserve of water is available to avoid running out of water during a test.

2. Determine the test zone. The test section length should be a minimum of 5 times the diameter of the borehole. Avoid placing the packer in a zone of fractured rock or in the bottom of the casing because leakage will occur. Keep the rock core or drilling logs handy to refer to during the test.

3. Maintain the test pressures below what is commonly referred to as the Maximum Water Pressure (Pmax). This should avoid the chance of hydrofracturing (loosening) the rock mass. Pmax is determined by the following formula:

$$Pmax = (H_1)\ (1\ psi/ft)$$

(Note: in highly fractured rock this should not exceed 0.75 psi/ft.)

where,

H_1 = depth in feet from ground surface to the bottom of the upper packer

During test operations the water pressures are observed at the gauge. The Maximum Gauge Pressure (GPmax) is calculated by the following formula:

$$Gpmax = (H_1+H_3)\ (1\ psi/ft) - (H_1-H_2)\ (.43\ psi/ft)$$

where,

H_1 = depth in feet from ground surface to the bottom of the upper packer

H_2 = depth in feet from ground surface to the static water level

H_3 = height in feet of pressure gauge above ground surface

The depth and height variables (H_1, H_2 and H_3) are shown on Figure 5.4-2.

When significant flow rates are encountered during the test the gauge pressure may need to be increased to compensate for system pressure loss due to frictional head loss. This is an unusual situation.

4. To ensure that the packer system is not leaking, test it prior to the start of the actual permeability test. This can be done by installing the packer in a piece of steel casing and conducting the test as if it were being done in the borehole. The water pressure must not exceed the Packer Inflation Pressure (see Step #5, below). Calibration for a particular test assembly can be obtained on site by laying the system out on the ground and pumping water through the system while collecting the data as if the test were being performed in-situ. Check the hose for leaks. Check the water meter to assure that it is working properly.

5. Determine the Packer Inflation Pressure (PIP), by performing the following steps:

Step 1 - Establish Minimum Inflation Pressure (MIP) (i.e., the pressure required to inflate the packers in the casing so that they can no longer be pushed or pulled through the casing)

Step 2 -Establish the Static Head Pressure (Ps) in psi at the test depth by the following calculation:

$$Ps = (H_1-H_2)\ (0.43\ psi/ft)$$

where,

H_1 and H_2 are as above

Step 3 - Make sure the Packer Inflation Pressure (PIP) equals the Minimum Inflation Pressure (MIP) plus the Static Head Pressure plus the Maximum Gauge Pressure (Gpmax) of the test zone between the packers. This is sometimes written as follows:

$$PIP = MIP + Ps + Gpmax$$

6. Determine the static water level in the borehole prior to the installation of the packer.

7. Assemble and install the packer equipment in the borehole. Measure each rod to top of coupling as it goes into the hole. Be sure rods are tightened to prevent leakage at the joints; teflon tape may be helpful. Number the rods for easy tracking of the packer location for sequential tests. Lower the equipment to the location of the deepest test. Figures 5.4-1 and 5.4-2 depict configurations for mechanical and pneumatic packer tests.

8. Before performing the first test, bleed air out of the lines by forcing water through the packer system assembly before the packers are inflated. Inflate both packers to the required packer pressure. Double packers are usually spaced five feet apart, but spacing can be varied to meet specific test requirements.

9. Before starting the test, review the Packer Test Data Sheets (Figure 5.4-3) and record the following:

   - Test number
   - Test section (i.e., length)
   - Hole size
   - Height of pressure gauge above ground surface
   - Ground surface elevation
   - Depths to rock surface, ground water, bottom of boring, bottom of upper packer, and to top of lower packer

10. Conduct the bedrock packer test in three stages:

    Step 1 - 1/2 Gpmax

    Pump water into the system and record observations of gauge pressure and water meter at 30-second intervals for at least three to five minutes after a constant rate of flow is reached.

    Step 2 - Full Gpmax

    Pump water into system and record observations of gauge pressure and water meter at 30-second intervals for at least three to five minutes after a constant rate of flow is reached.

    Step 3 - Full Gpmax plus 20 psi increase on the Packer Inflation Pressure

    Increase Packer Inflation Pressure by 20 psi. Pump water into the system and record observations of gauge pressure and water meter at 30-second intervals for at least three to five minutes after a constant rate of flow is reached. The results of Steps 2 and 3 should be similar. If they are not, Step 3 should be repeated, increasing the Packer Inflation Pressure by an additional 20 psi. This is done to check for leakage past the packers.

    For all test steps, record water levels in the casing during the test. If the water level rises or bubbles appear during the test, the packers may not be sealed and the test results may be suspect. Measurements of doubtful accuracy must be noted, along with a description of the questionable aspects. If possible, testing should be continued until accurate data is obtained. It may be necessary to move the packer assembly a short distance to obtain an adequate seal.

11. If leakage of water from the packed section into the surrounding rock is so great that the Gpmax cannot be reached, run the pump at its full capacity with the bypass valve closed. Record the volume of water pumped into the test section and the associated pressure readings at timed intervals. This data will give a minimum value of the rock permeability.

12. Upon completion of the test, deflate the packers and move to the next test depth. Complete log sheets (see Figure 5.4-3).

13. The same test methodology may be used with a single packer. Single packer tests are conducted either as the borehole is advanced or after the entire borehole has been completed. With this test configuration the bottom of the borehole takes the place of the second packer.

5.4-3 COMPUTED ROCK MASS PERMEABILITY

Compute the rock mass permeability. Additional data required for each test are as follows:

(1) depth of hole at time of each test;
(2) depth to bottom of top packer;
(3) depth to top of bottom packer;
(4) depth to water level in borehole at frequent intervals;
(5) elevation of potentiometric level;
(6) length of test section;
(7) radius of hole;
(8) length of packer;
(9) height of pressure gauge above ground surface;
(10) height of water swivel above ground surface; and
(11) description of material tested.

Item (4) is important since a rise in water level in the borehole may indicate leakage from the test section or an interconnected bedrock fracture pattern. A sketch of the test equipment arrangement showing the relative portions of the components should be made for each configuration used. (See Figure 5.4-3, page 3 of 3.)
The formulas used to compute the permeability from pressure test data are:

$$K = (Q/2\pi LH)\ \ln(L/r)$$

When $L > 10r$ (the above formula is used when the length is greater then ten times the radius)

and,

$$K = (Q/2\pi LH)\ \sinh^{-1}(L/2r)$$

When $10r > L > r$(the above formula is used when the length is greater than the radius but less the ten times the radius)

where,

K = permeability
Q = constant rate of flow into the hole
L = length of the test section
H = differential head on the test section
r = radius of the borehole

It should be noted that when the test is conducted above the water table H is the distance from the water pressure gauge to the middle of the test section. When the test is below the water table H is the distance from the gauge to the static water level.

While the above formula is most often used with a double packer arrangement, it also applies for use with a single packer. With a single packer the length of the test section (L) is not fixed (as with the double packer arrangement) and is equal to the distance from the bottom of the packer to the bottom of the hole.

These formulas provide only approximate values of K since they are based on several simplifyin0g assumptions and do not take into account the flow of water from the test section back to the borehole (U.S. Bureau of Reclamation, 1977).

However, they give values of the correct order of magnitude and are suitable for practical purposes. Table 5.4-1 (Haley and Aldrich, 1977) provides a general grouping of rock mass permeability.

5.4-4 PROBLEMS AND POSSIBLE SOLUTIONS

There are a number of possible problems that may develop while performing a bedrock packer test. Several of the most common problems and their possible solutions are outlined below.

1. Packers move up out of the hole at the start of the test.

Occasionally, particularly in low permeability rocks, the packer assembly may lift out of the hole due to the water pressure. Observers should stay clear of the top of the borehole to avoid injury. It may be helpful to deflate and re-inflate the packers to obtain a more positive seal in the borehole. Also, the rig drive head can be placed over the top of the swivel to help to hold the packers in place during the testing.

2. Excessive amounts of water are pumped into the formation.

In certain types of hydrogeologic or contaminant investigations, large quantities of water should not be pumped into the aquifer as this may impact local ground water quality and movement. If this is a concern, packer tests should be avoided. Alternatively, falling or rising head tests may be performed or geophysical borehole data may be obtained.

3. The packers jam in the borehole.

Packers may become caught in the borehole for two reasons: 1) caving of the formation around the packers, or 2) failure of the packers to deflate. In the latter case, it is generally advisable to re-inflate and deflate the packers a second time to try to remedy the problem. Forcibly removing the packers from the hole should be avoided as they may become permanently lodged or damaged. In some instances it may be helpful to pump water through the system to help lubricate the equipment for removal. Packer tests in soft, broken or cavernous formations should always be attempted with great caution.

4. Water meter malfunctions.

Water meters are sensitive instruments and are subject to malfunctions due to clogging by debris or mechanical failure. It is important to check the water meter prior to use to be certain that it is working properly. Generally, it is best to place the water meter in a horizontal position, particularly for low flow measurements. It is also important to determine what the units of the meter dial are prior to use, as they are often poorly marked. Discharging water from the meter into a container of known volume (e.g., 5-gallon bucket or a 55-gallon drum) and comparing this to the metered volume provides a reasonably accurate check.

REFERENCES

Haley and Aldrich Inc., 1977, Manual of field procedures, procedure no. 27, water pressure test (rock): Cambridge, MA.

U.S.Bureau of Reclamation, 1977, Ground water manual: Denver, CO, U.S. Government Printing Office, 783 p.

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U.S.Bureau of Reclamation, 1974, Earth manual, Washington: DC, U.S. Government Printing Office, 810 p.

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SECTION 5.4
PACKER TESTS

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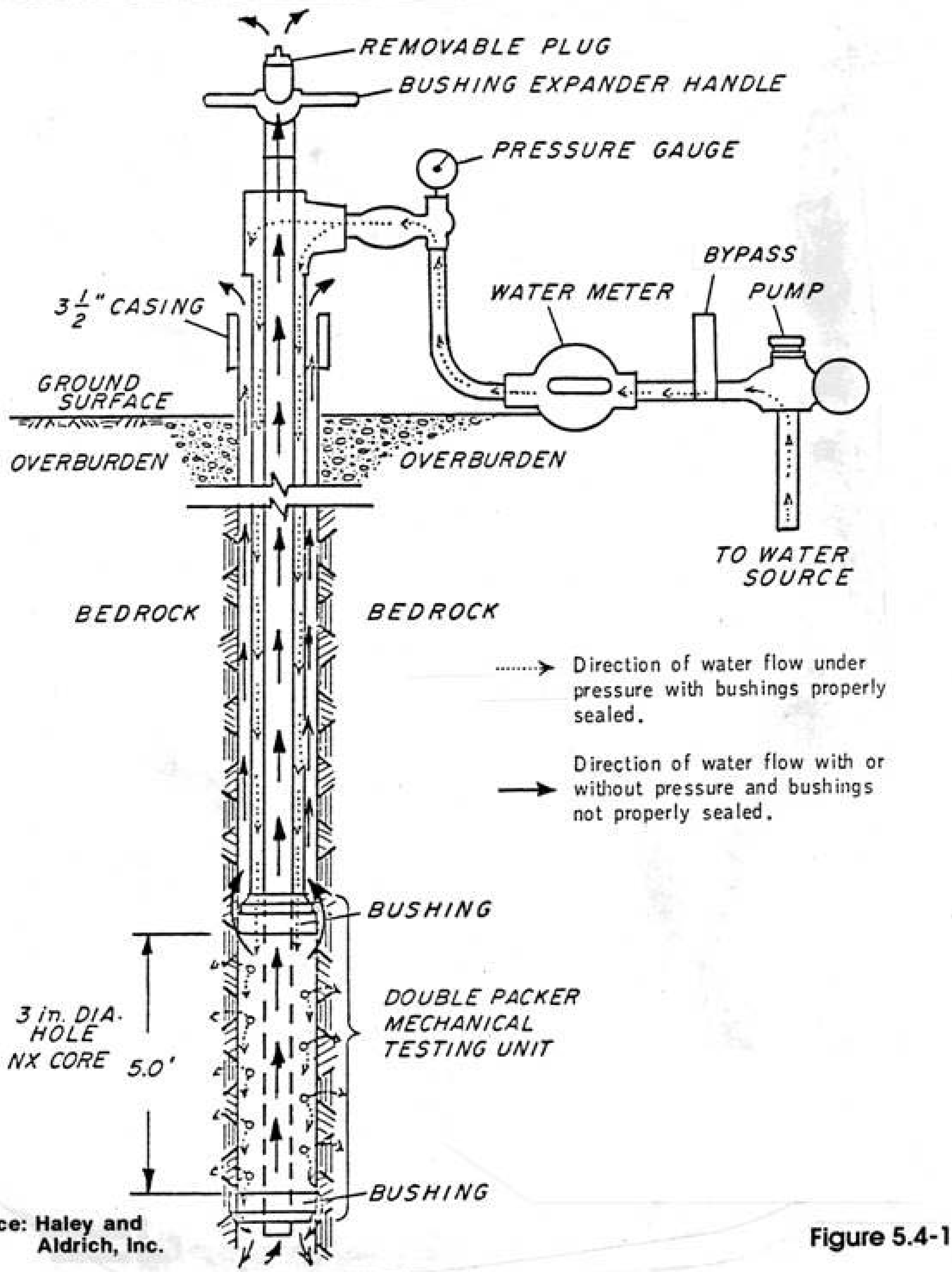
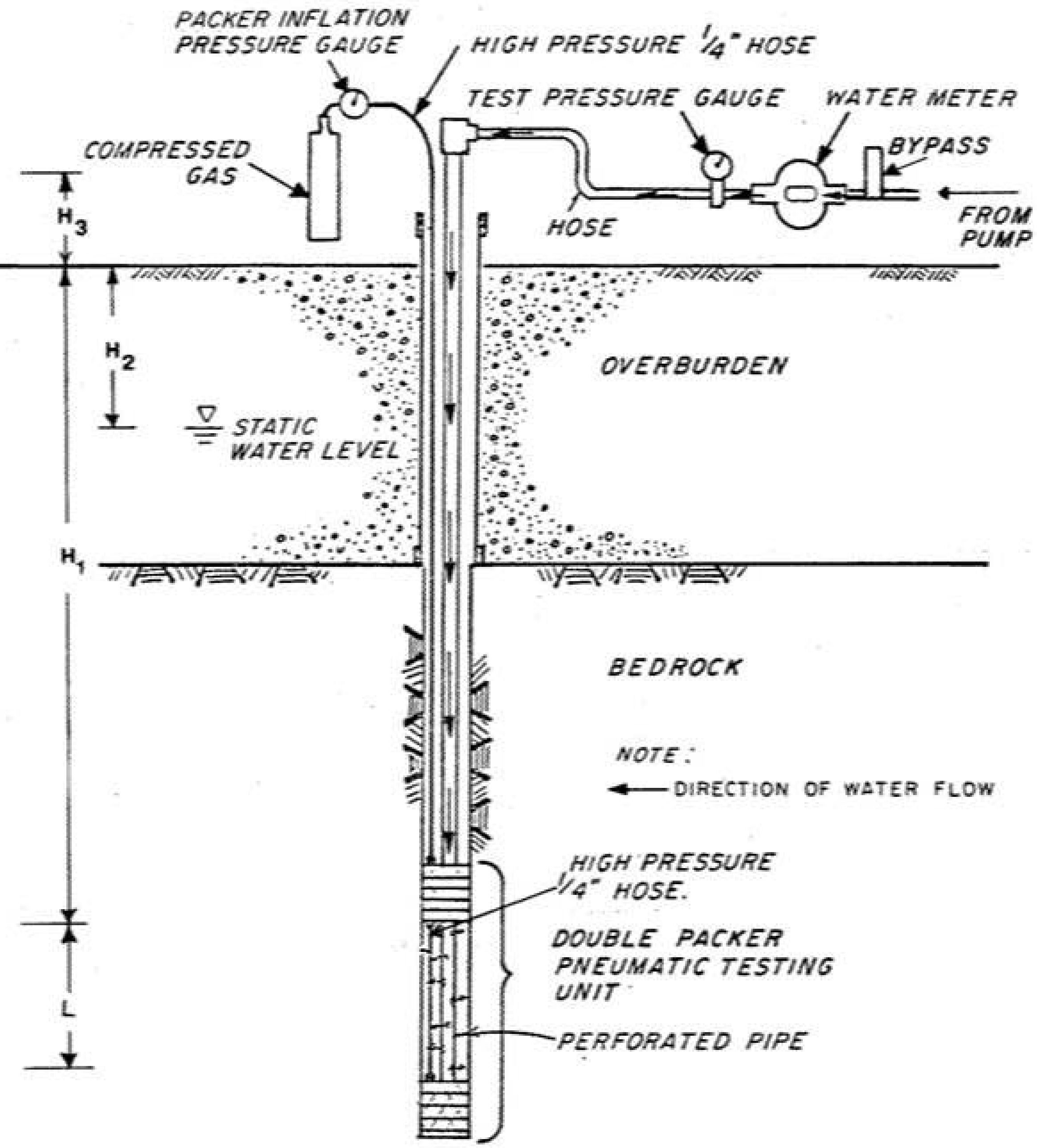


Source: Haley and Aldrich, Inc.

Figure 5.4-1

Schematic of Mechanical Packer Pressure Test and Related Equipment.



Source: Haley and Aldrich, Inc.

Figure 5.4-2

Schematic of Pneumatic Packer Test and Related Equipment.

WATER PRESSURE TEST

HOLE NO. | TEST NO.

PROJECT:
CLIENT:
CONTRACTOR:

JOB NO.
SHEET NO.
LOCATION:
ELEVATION:
DATE START:
DATE FINISH:
DRILLER:
INSPECTOR:
GEOLOGIST:

	PACKER SYSTEM	WATER METER	WATER GAUGE	SURGE CHAMBER
TYPE				
MFG.				
MODEL NO.				

M.G.P. = (0.566 to 1.0) x 2
COMPUTED MAX GAUGE PRESS: (MGP)
COMPUTED INTERNAL FRICTION:

ROCK TYPE: HOLE SIZE
RECOVERY (%)
R Q D (%)

DEPTHS: (All Distances Measured From Ground Surface In Feet)

TO TOP OF ROCK
TO BOTTOM OF BORING
TO WATER TABLE
TO TOP LOWER PACKER
TO BOTTOM UPPER PACKER (2)
LENGTH OF TEST SECTION
HEIGHT OF WATER PRESSURE GAUGE ABOVE GROUND SURFACE

TIME	ELAPSED TIME (MIN)	PACKER PRESSURE (PSI)	GAUGE PRESSURE (PSI)	METER READING (GALS)	VOLUME OF FLOW (GALS/MIN)	REMARKS

Figure 5.4-3
Page 1 of 3
Example of Packer Test Data Sheet.

Source: Weston Geophysical

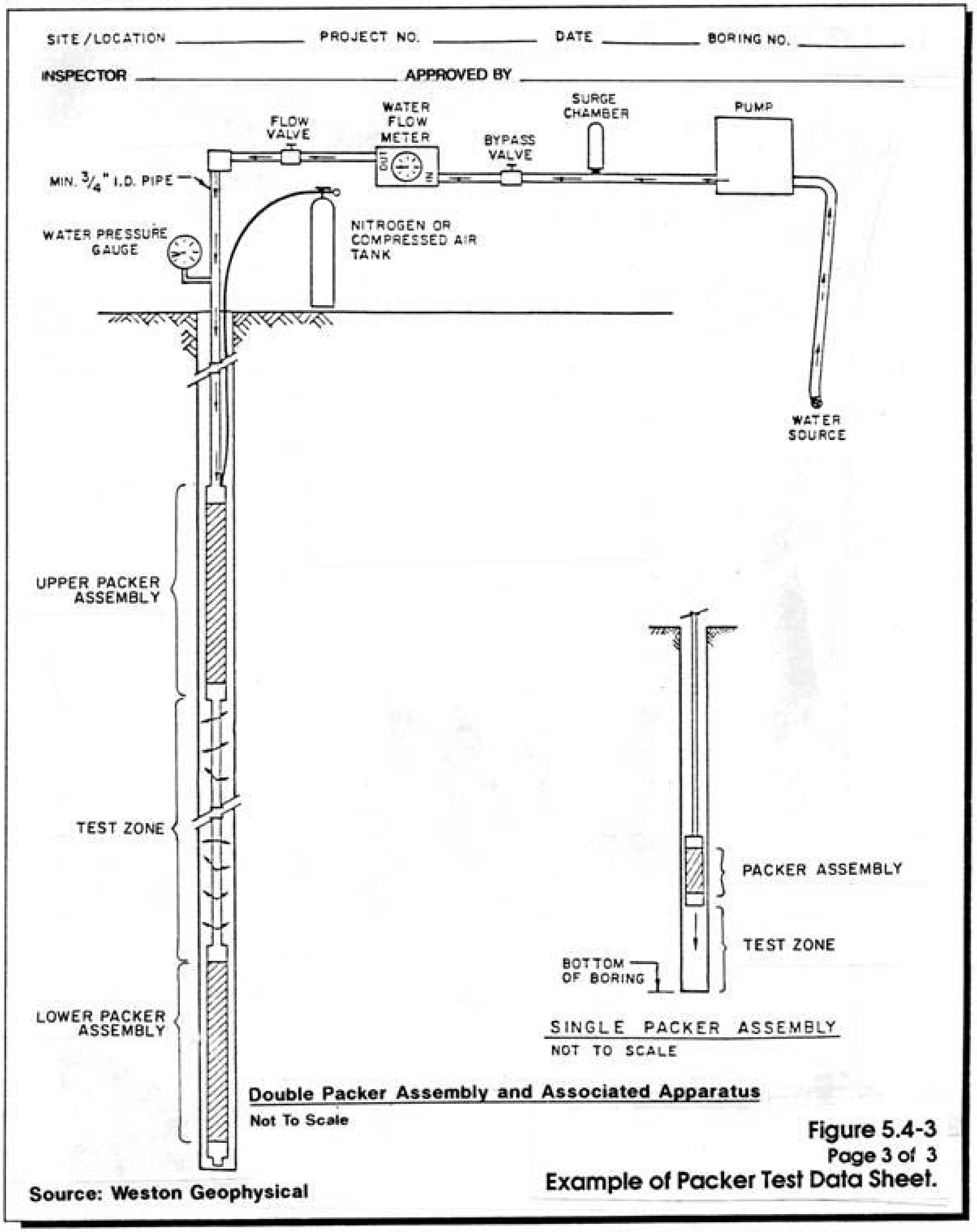
WATER PRESSURE TEST

Project____________________ Boring No. ____________ Test No. ____________

TIME	ELAPSED TIME (MIN)	PACKER PRESSURE (PSI)	GAUGE PRESSURE (PSI)	METER READING (GALS)	VOLUME OF FLOW (GALS/MIN)	REMARKS

Source: Weston Geophysical

Figure 5.4-3
Page 2 of 3
Example of Packer Test Data Sheet.



Double Packer Assembly and Associated Apparatus
Not To Scale

Figure 5.4-3
Page 3 of 3
Example of Packer Test Data Sheet.

Source: Weston Geophysical

Description	Range
Very low (equivalent to clay)	Less that 1 x 10^{-7} cm/sec
Low (equivalent to silt)	1 x 10^{-5} to 1 x 10^{-7} cm/sec
Medium (equivalent to fine sand)	1 x 10^{-4} to 1 x 10^{-5}cm/sec
High (equivalent to sand)	1 x 10^{-2} to 1 x 10^{-4} cm/sec
Very high (equivalent to clean sand or gravel)	More than 1 x 10^{-2} cm/sec

Table 5.4-1
General Grouping of Rock Mass Permeability

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STANDARD REFERENCES FOR MONITORING WELLS

SECTION 5.5 SURVEYING AND DATUM PLANES

SECTION 5.5
SURVEYING AND DATUM PLANES

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5.5 SURVEYING AND DATUM PLANES

5.5-1 PURPOSE

The purpose of this section is to present the minimum requirements for establishing horizontal and vertical surveying control for exploration programs that will satisfy the requirements of the Commonwealth's new computerized Geological Information System (G.I.S.). Accurately surveyed locations of explorations are a key element in the evaluation of all field data and are necessary for the preparation of geologic profiles and the interpretation of vertical and horizontal ground water flow directions. The accuracy of measurements and established elevations is particularly important when ground water gradients are low, as errors may easily lead to misinterpretation of the direction of ground water flow. The survey is usually performed after the explorations have been completed. Explorations and land features requiring accurate horizontal and vertical control are:

- Borings
- Test pits and trenches
- Monitoring wells and piezometers
- Geophysical surveys
- Surface water and drainage features
- Buildings and underground tanks

5.5-2 METHODOLOGY

The project manager shall go over the survey program with the survey chief to be sure that all requirements are understood and that the survey crew is alerted to potential site hazards. The following criteria should be met for <u>all</u> survey programs.

1. The survey is to be performed by registered professional land surveyors or civil engineers.

2. The survey shall be accurately performed to a precision of 0.01 foot for vertical control and 1.0 foot for horizontal locations.

3. Horizontal control is to be tied into either the USGS grid or the UTM grid coordinate system. Mean Sea Level (NGVD, 1929) should be used as the vertical datum.

4. Elevation precision to be obtained at monitoring wells and piezometers shall be:

- o Top lip of protective casing without cover (0.01 foot); this point should only be used for vertical control and not for water-level measurements

- o Top of monitoring well riser pipe (0.01 foot); a permanent reference point should be marked on the top of the riser to be used as the measuring point for all water-level measurements

5. Mark clearly a permanent site benchmark at the site on the most stable nearby feature and note its location on survey maps.

6. The surveyor should submit, as part of the survey report, a copy of all original field notes, including a description of the measuring points at all monitoring wells to make certain that the elevation has been assigned to the correct point.

7. Survey information needs to be reviewed carefully with respect to horizontal and vertical determinations. Survey errors may often be caught by using relative distances between wells or noting apparent anomalies in water levels or flow directions. The survey should proceed in a manner that closes out the loop so that one can detect errors. Check to see that all survey traverses have been closed on the original benchmark or reference point to within acceptable limits.

5.5-3 PROBLEMS AND POSSIBLE SOLUTIONS

5.5-3.1 Previous Use of a Datum Other Than Mean Sea Level

Many times a parcel of land contains a previously established permanent benchmark on-site to which all vertical elevations have been referenced. Such an arbitrary local datum may not provide any specific information about its relationship to the USGS datum Mean Sea Level (MSL), the standard National Geodetic Vertical Datum (NGVD) of 1929. An arbitrary datum, when used, should be designated by the letters L.D., for Local Datum; in the past, this designation often has been omitted. In other cases, a standard city-wide local datum is used; this carries a known and published relationship to the USGS datum.

Surveys at all sites subject to DEP review shall be referenced to Mean Sea Level. Due to the requirements of the Department's computerized mapping program, the Department can only accept information that is expressed in terms of the USGS datum. Fortunately, Massachusetts is liberally endowed with reference elevation benchmarks. Therefore, it should not be too difficult to convert a local datum to the USGS standard.

5.5-3.2 Weather Conditions

Inclement conditions increase the chance for errors in identification, measurement, and recording. Surveyors need to take extra time to assure proper identification of all monitoring wells surveyed, to guarantee ice-and snow-free surface elevation shots, and to carefully record survey data despite adverse conditions. Obtaining stable tripod set-ups may be more difficult under these conditions. Sightings should use shorter distances than under more favorable conditions. Warm, sunny days generate heat waves that may present problems for optical instruments.

5.5-3.3 Work at Hazardous Waste Sites

Surveyors need to be made aware of hazardous site conditions and potential exposures. Surveyors should have been enrolled in a health monitoring program for any sites which require personal protection above Level D (see Section 2.3 Health and Safety). Note that anticipated risks to surveyors would be expected to be less than for those engaged in collecting samples or in subsurface explorations. However, potential surface contact with hazardous materials should be pointed out and appropriate protective equipment worn and used. Surveyors shall also be made aware of other site activities and procedures for evacuation in case there is a release elsewhere on-site which triggers implementation of site evacuation or other contingency plans.

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SECTION 6.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

SECTION 6.1
QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

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6.1 QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

6.1-1 DEFINITIONS

The following definitions are used in Sections 6.1-6.5, inclusive.

Accuracy - the degree of agreement of a measurement with an accepted reference value. Accuracy is generally reported as percent recovery, and calculated as:

$$\frac{\text{Measured Value}}{\text{Accepted Value}} \times 100$$

Analyte - the chemical or property for which a sample is analyzed.

Comparability - the expression of information in units and terms consistent with reporting conventions; the collection of data by equivalent means; or the generation of data by the same analytical method. Aqueous samples shall be reported as g/l solid samples shall be reported in units of mg/kg, dry weight.

Completeness - the percentage of valid data obtained relative to that which would be expected to be obtained under normal conditions. Data are judged valid if they meet the stated precision and accuracy goals.

Duplicate - two separate samples taken from the same source by the same person at essentially the same time and under the same conditions that are placed into separate containers for independent analysis.

Episode - a continuous period of time during which sampling activities are undertaken. Cessation of activities for more than 48 hours terminates the episode.

Precision - a measure of the agreement among individual measurements of the same property under prescribed similar conditions. Precision is generally reported as Relative Standard Deviation (RSD) or Relative Percent Difference (RPD). Relative standard deviation is used when three or more measurements are available and is calculated as:

$$\text{RSD} = \frac{\text{Standard Deviation}}{\text{Arithmetic Mean}} \times 100$$

Relative percent difference is used for duplicate measurements and is calculated as:

$$\text{RPD} = \frac{\text{Value 1 - Value 2}}{\text{Arithmetic Mean of Values 1 and 2}} \times 100$$

Quality Assessment - the overall system of activities that provides assurance that quality control activities are done effectively.

Quality Assurance (QA) - all the means taken inside and outside the laboratory to make certain that all laboratories use the same calibration and standardization procedures for reporting results; also, a program which integrates the quality planning, quality assessment, and quality improvement activities within an organization.

Quality Control (QC) - all the means taken by an analyst to ensure that the total measurement systems are calibrated correctly. It is achieved by using EPA reference standards, duplicates, replicates, and sample spikes. Also, the routine application of procedures designed to ensure that the data produced achieve known limits of precision and accuracy.

Replicate - two aliquots taken from the same sample container and analyzed separately. Where replicates are impossible, as with volatile organics, duplicates must be taken.

Rinse - fill container with approximately one-quarter of its total volume, cap and make certain that the rinsate makes contact with all interior surfaces.

6.1-2 QA/QC PLAN

Prior to the initiation of monitoring well sampling activities, a QA/QC Plan will be prepared. The purpose of this document is to provide to on-site personnel an immediate source of information relevant to the work to be undertaken, as well as to initiate the planning and logistics required for a successful sampling episode.

The plan will include, as a minimum:

- Site identity
- Project organization and responsibilities
- Laboratory/shipping information
- Project and data quality objectives
- Chain of custody and sample identification procedures
- Parameters for analysis
- Analytical program with identification of analytical methods
- Field QC samples required
- Sampling and preservation procedures
- List of required equipment
- Equipment decontamination sequence and location
- Calibration of field measurement equipment
- Data quality requirements and assessments
- Signature Block

A sample format, for such a checklist and form, is provided in Appendix A.

6.1-3 FIELD QC SAMPLES

A variety of QC samples are collected in the field and submitted for laboratory analysis. These samples are intended to assess the effectiveness of equipment decontamination, the precision of sampling efforts, the effects of ambient environmental conditions on sensitive analytes (e.g., volatile organics analysis or VOA), and the potential for contaminants attributable to reagents or decontamination fluids. Identifying such potential sources of error is essential to the success of the sampling program and the validity of the environmental data. Each QC sample is described below. As a minimum, each set of ten or fewer field samples should include a trip blank, a duplicate and one sample collected in a sufficient volume to allow the laboratory to perform a matrix spike.

6.1-3.1 Trip Blanks

Trip blanks are samples that originate from analyte-free water taken from the laboratory to the sampling site and returned to the laboratory with the volatile organic samples. One trip blank should accompany each cooler containing volatile organics (VOAs); it should be stored at the laboratory with the samples, and analyzed with the sample set. Trip blanks are only analyzed for VOAs.

6.1-3.2 Equipment Rinsates

Equipment rinsates (sometimes referred to as "equipment blanks" or "sampler blanks") are the final analyte-free water rinse from equipment decontamination in the field and are collected at least once during a sampling episode. If analytes pertinent to the project are found in the rinsate, the results from the blanks will be used to qualify the levels of analytes in the samples. This qualification is made during data validation. The rinsates are analyzed for the same analytes as the samples that have been collected with that equipment. If dedicated sampling equipment is used, this protocol becomes redundant.

6.1-3.3 Field Blanks

Field blanks, also known as source water samples, are samples of the water used in decontamination and steam cleaning in the field. At a minimum, one sample from each episode and each source of water will be collected.

6.1-3.4 Field Replicates and Duplicates

Field Replicates for water samples, except VOA samples, are collected, homogenized, and then split. VOA samples are not mixed, but taken as grab samples. The replicates for water samples should be collected sequentially. Field replicates should be collected at a frequency of 10% per sample matrix (i.e. water or soil) or one replicate for every 10 samples.

To maximize data utility when sampling for analysis by USEPA's Contract Laboratory Program (CLP), which is generally used for litigative quality investigations, the same samples used for field replicates should be taken in sufficient volume to be split by the laboratory and be used as the laboratory replicate or matrix spike. This means that for designated samples, there will need to be a volume sufficient for the normal sample analysis, the field duplicate analysis, and the laboratory matrix spike/ matrix spike duplicate analysis (i.e., up to three times the single sample volume).

Field duplicates are a second aliquot of a sample taken in the field that is treated the same as the original sample in order to determine the precision of the method. They shall be analyzed with every analytical batch or every 20 samples, whichever is greater. This procedure is applicable to all organic and inorganic chemical analytes.

6.1-4 SAMPLE CONTAINER REQUIREMENTS

Sample integrity is assured by use of containers appropriate to both the medium/matrix to be sampled and the analytes of interest. For example, samples intended for semi-volatile organic analyte (SVOA) analyses are collected in glass bottles with teflon-lined caps; samples for volatile organic analyte (VOA) analyses are collected in teflon-septum-capped glass vials with "zero" headspace to minimize diffusive and evaporative losses; and most samples for inorganic analyses are collected in linear polyethylene bottles. Sample containers must be prepared in the laboratory in a manner consistent with USEPA protocols. DEP-approved preparation methods are described below. Bottles may also be purchased precleaned and QC-checked from commercial suppliers. It is generally less expensive and more efficient to purchase the precleaned containers. If precleaned containers are used, the lot number should be reported on the chain-of-custody.

6.1-4.1 Preparation of Sample Containers

Containers should be cleaned based on the analyte of interest. Bottles used to collect hazardous wastes are generally only used once and then discarded.

6.1-4.1.1 Preparation of Containers for Semi-volatile Organic Analyte

Included in this section as semi-volatile organics are: base-neutral extractables, PCBs, pesticides and herbicides. Requires 2-liter amber glass bottles for water samples and 8 oz. clear glass jars for soil, sediment, and sludge samples.

1. Wash containers, closures, and teflon-lined caps in hot tap water with laboratory grade non-phosphate detergent (e.g. Alconox or equivalent).

2. Rinse three times with tap water.

3. Rinse three times with ASTM Type I deionized water.

4. Rinse with technical-grade acetone.

5. Rinse with pesticide grade hexane.

6. Air dry in a contaminant-free environment to get rid of any vapors.

7. Oven dry the glass containers only (1 hour at 105^{o} C).

8. Remove glass containers from oven.

9. Loosely screw teflon-lined caps on containers. Attendant to wear gloves to prevent recontamination; containers not to be removed from preparation room until sealed.

6.1-4.1.2 Preparation of Containers for Metals and Cyanide Analytes

For metals: requires 1-liter clear glass or polyethylene bottles for water samples and 16 oz. clear glass or polyethylene jars for soil, sediment, and sludge samples. For cyanides: requires 1-liter amber glass or polyethylene bottles for water samples and 16 oz. amber glass or polyethylene jars for soil, sediment or sludge samples.

1. Wash bottles and closures in hot tap water with laboratory grade non-phosphate detergent (e.g. Alconox).

2. Rinse three times with tap water.

3. Rinse with 1:1 nitric acid.

4. Rinse three times with tap water.

5. Rinse with 1:1 hydrochloric acid.

6. Rinse three times with ASTM Type II deionized water.

7. Air dry in contaminant-free environment.

8. Place closures on bottles. Attendant to wear gloves to prevent recontamination; bottles not to be removed from preparation room until sealed.

6.1-4.1.3 Preparation of Containers for Volatile Organic Analytes

Requires (2) 40-ml glass vials per water sample and 8-oz wide mouth glass jars with teflon liner for concentrated waste samples.

1. Wash vials, septa, teflon liners, and closures in hot tap water with laboratory grade non-phosphate detergent (e.g. Alconox).
2. Rinse three times with tap water.

3. Rinse three times with ASTM Type I deionized water.

4. Oven dry (in a muffle furnace) the glassware only (1 hour at 105^{o} C).

5. Rinse septa, teflon liners, and closures in methanol.

6. Air dry septa, teflon liners, and closures in a contaminant-free environment.

7. Remove vials and jars from oven.

8. Place septa in closures, teflon side down to face the sample, and place on vials. Put teflon-lined caps on jars. Attendant to wear gloves; vials and jars not to be removed from preparation room until sealed.

6.1-5 PREPARATION OF PUMP TUBING

Adequate lengths of 3/8-inch ID teflon tubing and/or 3/8-inch ID silicone tubing will be prepared by the sampling crew for each sampling episode which requires tubing. Teflon tubing is preferred and can be reused. If tubing shows wear, then discard. A specific procedure for preparing teflon tubing for VOA analysis follows.

The VOA Teflon tubing preparation procedure is as follows:

1. Pump non-phosphate detergent solution (e.g. Alconox) through system for two minutes.

2. Pump clean hot tap water through system for two minutes or until clear, whichever is longer.

3. Pump technical grade acetone through system for two minutes.

4. Pump pesticide grade hexane through system for two minutes.

5. Pump ASTM Type II deionized water through system for five minutes.

6. Seal tubing ends, close with teflon caps (no wrapping with plastic wraps or "baggies"), and label with date of cleaning.

A general (suitable also for silicone) tubing preparation procedure is as follows:

1. Pump non-phosphate detergent solution through system for two minutes.

2. Pump clean hot tap water through system for two minutes or until clear, whichever is longer.

3. Pump analyte-free water through system for two minutes.

4. Pump decontamination fluid specified in the site-specific Quality Assurance Plan through system for two minutes.

5. Pump analyte-free water through system for two minutes.

6. Seal tubing ends; wrap (no "saran wrap" or "baggies") and label with date of cleaning.

6.1-6 FORMS AND RECORDS

Documentation of the activities surrounding well purging sample collection, sample preservation, chain of custody, and equipment calibration is critical to subsequent data evaluation and utility. Field data must be recorded in ink in a bound field notebook. Data may be transferred to forms such as those shown in Section 6.2 for ease of calculation and filing.

APPENDIX A

QUALITY ASSURANCE/QUALITY CONTROL CHECKLIST AND FORM FOR SAMPLING MONITORING WELLS

Quality Assurance/Quality Control Checklist
And Form For Sampling Monitoring Wells

A. Project Identity, Organization and Responsibilities

1. Project Identity

Project Name:__________________ Project ID Number:__________________

Address:________________________ Date of Sampling:__________________

____

____

Map Coordinates:________________ UTM or Lat/Long (circle one)

Site Description:____

____

2. Personnel (contact name, firm and telephone number)

Project/site manager:_______________________________________

____

Health and Safety Officer:___________________________________

____

Quality Assurance Officer:__________________________________

____

Field Leader:____

____

Sampling Personnel:_______________________________________

____

Well Driller:____

____

Consultant Firm:____

____

Laboratory Performing Analysis:_______________________________

____

Laboratory Shipping Address:__________________________________

____

____

B. Project and Data Quality Objectives

1. Project Description

Objective and Scope Statement:________________________________

____

____

____

Monitoring Network Design and Rational:______________________

____

____

____

Health and Safety Plan to be used at Site:__________________

Level A, B, C, or D:__________Level

2. Data Quality Objectives

Objective of Field Sampling/Data Usage:______________________

____

____

____

C. Chain of Custody and Sample Identification Procedures

Chain of Custody Required:___________ (yes or no)

Sample Custody Procedures:_______________________________________

____

____

Sample Identification Procedures:________________________________

____

____

____

D. Parameters for Analysis

Monitoring Parameters and Their Frequency of Collection

Monitoring Parameters	Their Frequency of Collection
______________________	____________________________
______________________	____________________________
______________________	____________________________
______________________	____________________________
______________________	____________________________
______________________	____________________________

E. Parameter Table

Parameter	Number of Samples	Sample Matrix	Analytical Method Ref	Sample Preservation	Holding Time
_________	_________	______	__________	___________	_______
_________	_________	______	__________	___________	_______
_________	_________	______	__________	___________	_______
_________	_________	______	__________	___________	_______
_________	_________	______	__________	___________	_______
_________	_________	______	__________	___________	_______

F. Number of Samples, Blanks, Duplicates, and Matrix Spikes

Matrix: Parameter	Number of Samples	Trip Blanks[1]	Equip Rinsates[2]	Field Blank[3]	Field Replicates[4]	MS/ MSD[5]	Total
________	________	______	________	______	________	___	_____
________	________	______	________	______	________	___	_____
________	________	______	________	______	________	___	_____
________	________	______	________	______	________	___	_____

1 Trip Blanks: One trip blank per cooler containing VOAs
2 Equipment Rinsates: At least one per sampling episode
3 Field Blanks: At least one per sampling episode and per source of water
4 Field Replicates: One for every ten samples
5 MS/MSD: Matrix spike and matrix spike duplicates samples are collected at a rate of one each per 20 samples

G. Sampling, Preservation, and Decontamination Procedures

1. Sampling Procedures:____

   ____

   ____

   ____

2. Preservation Procedures:____________________________________

   ____

   ____

   ____

3. Decontamination Sequence/Procedures:________________________

   ____

   ____

   ____

   Decontamination Location(s):________________________________

4. Calibration Procedures and Preventive Maintenance:__________

5. Equipment Needed for Sampling, Preservation, and Decontamination

Item and Description	Dedicated (Y/N)	Quantity	Remarks
(ex: bailer, 1 liter, teflon)			
(bottles, 1 liter, amber glass)			
(DI water)			
(detergent solution)			
(Acetone)			
(filters)			
(data record forms)			
(plastic sheeting)			
(gloves)			
(pH/temp/Conductivity Meter)			
(Calibration Kits/ Standard Solutions)			

H. Data Quality Requirements and Assessments

Parameter	Sample Matrix	Detection Limit	Quantitation Limit	Estimated Accuracy	Accuracy Protocol	Estimated Precision	Precision Protocol
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________
________	______	________	__________	________	________	________	_________

Data Representativeness:____

____

____

____

H. Data Quality Requirements and Assessments (cont.)

Data Comparability:____

____

____

____

Data
Documentation:____

____

____

____

Data Reduction and Reporting:_____________________________________

____

____

____

Data Validation:____

____

____

____

I. Signature Block

Project Manager:

(print)	(signature)	(date)

Quality Assurance Manager:

(print)	(signature)	(date)

Field Leader:

(print)	(signature)	(date)

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 6.2 SAMPLING TECHNIQUES

SECTION 6.2
SAMPLING TECHNIQUES

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6.2 SAMPLING TECHNIQUES

6.2-1 INITIAL SETUP/EQUIPMENT CALIBRATION

Monitoring of ground water wells should proceed from the upgradient or background wells to the downgradient or contaminated wells as best as can be determined.

The area immediately surrounding the well should be cleared of debris and the ground surface covered with plastic sheeting to minimize contact of instruments with surface soils. The monitoring procedure is as follows:

1. Check the well for proper identification and location.

2. Measure and record the height of the protective casing above the ground.
3. After unlocking the well and removing any well caps, measure and record the ambient and well-mouth organic vapor levels using a Photoionization detector (PID). If a check for methane gas is required, then the use of a Flame Ionization Detector (FID) is necessary. If the ambient air quality at breathing level reaches an action level as described in the Health and Safety Plan, the sampler shall utilize the appropriate safety equipment.

4. Measure and record the distance between the top of the uncapped well and the top of the protective casing.

5. Measure from the top of the well casing to the static water level with accuracy to the nearest 0.01 foot. Then measure and record the depth to the bottom of the well. Upon removing the water level measuring device, rinse it with the decontamination fluid specified for the sampling episode and then either potable or deionized (DI) water, as specified for the episode.

6. Calculate the volume of standing water in the well by first determining the area:

   (1) Area = Xr^2

   where,

   X =3.142, and
   r =radius, measured as the diameter of the well divided by 2

   Calculate the volume of water in the well using the formula:

   (2) Volume = Area x h

   where,

   Area = surface calculated according to equation (1), and,

h = the distance between the water surface in the well and the bottom of the well.

Calibrate each piece of instrumentation prior to each day's use or as specified by its manufacturer. If possible, gross calibration may best be accomplished prior to the instrument leaving the office and then rechecked and fine-tuned on each day of sampling in the field. Each instrument should be recalibrated in the field on an as-needed basis. The recalibration frequency will depend on the number of measurements made, the time between measurements, and the type of samples. The operator's experience is also critical. Recalibration may be necessary before <u>each</u> measurement until the operator is confident that a particular instrument is stable.

Data are recorded, in ink in a field notebook and may be transferred to a form similar to that shown in Figure 6.2-1. The procedures described below apply to the specific instrument noted. If other instruments are used, similar procedures must be developed or the manufacturer's calibration procedures followed.

<u>6.2-1.1 Specific Conductance Temperature Meter (based on Y.S.I. S-C-T Meter, Model No. 33)</u>

<u>6.2-1.1.1 Temperature Probe</u>

1. Using a National Bureau of Standards-approved thermometer, immerse both temperature probes into a beaker of water and note any differences for the field probe.

2. Recalibrate as necessary.

3. Document calibration in a field notebook.

<u>6.2-1.1.2 Specific Conductance Meter</u>

1. Calibrate meter and probe using the calibration control and the red-line on the meter dial (Y.S.I. S-C-T Meter, Model No. 33).

2. Turn the function switch to read conductivity x10 and then depress the cell test button, noting the deflection. If the needle falls more than 2 percent of the reading, clean the probe and retest.

3. Using at least two standard solutions, which will most likely bracket the expected values for conductivity, note accuracy of the water and probe and clean probe if necessary. If stock standards are purchased or prepared by field personnel, they must be verified periodically against an EPA or NBS traceable standard.

4. Document calibration in a field notebook. Field notes should include: instrument serial number, the batch number of the calibration solutions and who did the calibration.

6.2.1.2 Calibration of Specific Ion Meter (pH/Eh Measurement)

6.2-1.2.1 pH Probe

1. If using refillable probes, remove electrode cap and check that filling solution is above the filling mark.

2. Immerse the probe in the pH 7 buffer solution and adjust the calibration control to read the appropriate pH. Check the pH buffer solution for correct pH value at the equilibrated temperature.

3. Remove the probe, rinse with distilled water and then immerse in either or both the pH 4 or pH 10 buffer solution, depending on the expected pH of the sample. Document calibration in a field notebook.

4. If the meter does not register the correct pH for that buffer solution, carefully adjust the calibration knob (i.e., slope control or sometimes called efficiency control) of the instrument to obtain the pH of the buffer.

5. After rinsing, insert the pH probe into the flow cell and allow the probe to come to equilibrium with the sample water.

6. Storage of the pH electrode should be in accordance with the manufacturer's instructions. These procedures vary from ambient air to specific storage solutions.

6.2-1.2.2 Eh/Platinum Probe

1. Check that the Eh or platinum probe is clean and the platinum band or tip is unoxidized. If dirty, polish with emery paper.

2. Immerse the probe and the reference probe, if required, into the calibration solution. Record the mV reading and the temperature and compare with the expected value (±10-20 mV).

3. Rinse the probe with distilled water and insert into the flow cell. Allow for temperature equilibration and record the sample Eh.

4. At the end of the day, the platinum probe should be stored in water.

6.2-1.3 Calibration of Photoionization Meters

6.2-1.3.1 HNU

On a daily basis, calibrate this instrument (manufactured by HNU Systems of Newton, Massachusetts) according to the following general instructions. See manufacturer's manual for more specific instructions. Note that the probe must be attached to the instrument in order to operate.

1. Turn the function switch to the "battery check" position. The needle on the meter should read within or above the green battery area on the scale plate. If the needle is in the lower position of the battery arc, the instrument should be recharged prior to any calibration. If red LED comes "on", the battery should be recharged.

2. Turn the function switch to the "on" position. In this position the UV light source should be on.

3. To zero the instrument, turn the function switch to the "standby" position and rotate the zero potentiometer until the meter reads zero. Clockwise rotation of the zero potentiometer produces an upscale deflection while counterclock-wise rotation yields a downscale deflection. If the span adjustment setting is changed after zero is set, the zero should be rechecked and adjusted if necessary. Wait 15-20 seconds to ensure that the zero reading is stable. If necessary, readjust the zero.

   The instrument is now ready for calibration by switching the function switch to the proper range.

4. Using non-toxic gas mixtures of known concentration available from the manufacturer in pressurized containers, connect the cylinder with the analyzed gas mixture to the end of the probe with a piece of tubing. Open the valve of the pressurized container until a slight flow is indicated and the instrument draws in the volume of sample required for detection. Now adjust the span potentiometer so that the instrument is reading the stated value of the calibration gas.

5 .If the instrument span setting is changed, the instrument should be turned back to the "standby" position and the electronic zero should be readjusted, if necessary. If the instrument does not calibrate, it may be necessary to clean the probe or the lamp connection. Record calibration information in a field notebook. Along with the instrument serial number, calibrating gas batch number, and the calibrator's name.

6.2-1.3.2 Photovac T.I.P.

On a daily basis, calibrate this instrument (manufactured by Photovac International of Huntington, New York) according to the following general instructions. See manufacturer's manual for more specific instructions.

1. Turn power switch on by first pulling the knob out and then up. Allow T.I.P. to warm up for five minutes prior to use. Turn span knob to max (9) and turn the zero knob to zero.

2. Attach "zero air" cylinder to T.I.P. inlet using PVC tubing. Zero instrument using zero knob only. (T.I.P. is very sensitive, so a stable reading of absolute zero is difficult and not necessary to achieve.)

3. Attach isobutylene cylinder to T.I.P. inlet. Use the span knob to adjust T.I.P. reading to the concentration number on the isobutylene cylinder (usually 60 ppm). Remove cylinder. T.I.P. is now calibrated and ready for use. Check randomly the calibration as T.I.P. has tendency to drift.

5. When finished, turn power off by pulling switch out and down. Recharge instrument overnight. Note that the Battery charger must be pushed into place and then screwed into bottom of T.I.P.

6.2-1.4 Calibration of Flame Ionization Detectors

6.2-1.4.1 OVA.

This instrument, manufactured by the Foxboro Co. of Foxborough, Massachusetts, is used for the rapid analysis of volatile organics in soil, water or air. Results obtained from soil/sediment samples are considered semi-quantitative.

1. Connect the appropriate probe to the Probe/Readout Assembly. Turn the pump switch on and leak check the flow system by plugging the end of the probe momentarily; the sample flow rate indicator should drop to zero. Turn the pump switch off. Turn INSTR switch on and allow 5 minutes for warmup. Turn the pump switch on and verify that the battery is charged.

2. Open the H2 tank valve and supply valve. Depress the igniter button. If the unit is in proper working order, the flame ionization detector will ignite in 1 to 6 seconds. Do not depress the igniter for more than 6 seconds. If the instrument does not light, allow it to run for several minutes and repeat the ignition procedure.

3. Check the calibration using a calibration check gas before and after use. Most units are factory calibrated to methane.

6.2-2 WELL PURGING

The following statement, taken from Handbook for Sampling and Sample Preservation of Water and Wastewater (EPA, 1982) summarizes the importance of well purging in order to obtain representative groundwater samples.

> "The importance of proper sampling of wells cannot be over emphasized. Even though the well being sampled may be correctly located and constructed, special precautions must be taken to ensure that the sample taken from that well is representative of the groundwater at that location and that the sample is neither altered nor contaminated by the sampling and handling procedure."

To obtain a representative sample of the groundwater it must be understood that the composition of the water within the well casing and in close proximity to the well is probably not representative of the overall groundwater quality at that sampling site. This is due to the potential presence of drilling contaminants near the well and because environmental conditions, such as the oxidation-reduction potential near the well, may differ from the conditions in the surrounding water-bearing materials. For these reasons it is frequently suggested that a well be pumped or bailed until it is thoroughly flushed of standing water and contains fresh water from the aquifer. The recommended length of time required to pump or bail a well before sampling is dependent on many factors including the characteristics of the well, the hydrogeologic nature of the aquifer, the type of sampling equipment being used, and the parameters being sampled. The time required may range from the time needed to pump or bail one bore volume to the time needed to pump several bore volumes. A common procedure is to pump or bail the well until a minimum of three to five bore volumes have been removed or the well has been bailed to dryness whichever comes first.

In order to calculate the one bore volume in the well the following formula should be used:

$$\text{Volume} = \pi r^2 h$$

where,

π =3.142,
r =radius, measured as the inside diameter of the well divided by 2
h =the distance between the water surface in the well and the bottom of the well.

Following the measurements and calculations described above, sampling will commence in the sequence below, utilizing the appropriate purging technique [1(a) through 1(d)]:

1. Lower the pump intake into the well. For shallow groundwater situations, the intake of the suction tubing or the submersible pump will be lowered to the top of the well screen and the well purged of the required volumes. Available alternatives to this procedure may be utilized in certain situations:

(a) If the well screen is 20 feet or longer (i.e., making pumping from the top impractical), the intake line should be lowered to the approximate mid-point of the screened portion of the well or in highly permeable formations. The intake portion can be moved up and down the entire water column.

(b) If the well is situated in tight formations such as tills, clays or rock, purging of the well should be performed near the top of the well screen. Pumping or purging at this level until one to three volumes have been purged will facilitate removal of standing well water without creating a large artificial gradient toward the well.

(c) Under certain circumstances, the pump intake may be placed just below the water surface and purging initiated. As the water surface lowers, the pump intake is lowered to remain below the water surface.

(d) When using a submersible pump in conjunction with an inflatable packer system, the packer should be placed just above the top of the well screen and inflated according to the packer manufacturer's instructions. The volume of stagnant water to be purged should be calculated based on the depth below the packer. The packer is not deflated until sampling is complete.

2. Connect the instrumentation header to the pump discharge and begin flushing the well. Monitor the in-situ parameters (pH, Eh, temperature, and specific conductivity) and measure the volume of groundwater being pumped. Alternatively, in-situ parameters may be monitored in a beaker filled from the pump discharge. Purging of the standing well water is considered complete when one of the following is achieved:

   o a minimum of three well volumes has been purged, and in-situ parameters have stabilized; or

   o five well volumes have been purged; or

   o the well has been pumped dry.

3. Record the in-situ parameters and the purging methodology utilized. All future sampling of this well must be preceded by the same purging method.

6.2-3 SELECTION OF SAMPLING EQUIPMENT

The sampling device to be utilized must be selected based upon both the physical characteristics of the well and the analytes to be determined. Aspects to be considered include:

- o analytes of concern
  - volatile organics
  - semivolatile organics
  - metals

- o depth to well screen relative to static water level

- o floating versus dissolved versus suspended contaminants versus non-aqueous liquids that are heavier than water

- o well diameter

- o safety

Typical sampling devices include and are further described below in Sections 6.2-3.1 through 6.2-3.4.

- o bailers
- o submersible pumps
- o peristaltic pumps
- o bladder pumps

Other pumps may be utilized for well purging but are not recommended for sample collection.

The following devices are generally <u>not</u> acceptable for collecting samples for analysis:

- o gas-driven piston pump
- o suction lift pumps
- o submersible diaphragm pump
- o gas-lift sampler
- o impeller pump

<u>6.2-3.1 Bailers</u>

Bailers (available in Teflon, PVC and stainless steel) are the only sampling devices currently recognized for sampling of volatile organics. However, their use is labor-intensive and may be discontinued after collecting samples for volatile organic analysis. Bailers may also enhance positive bias when multiple phases exist in a well. This condition should be evaluated prior to sampling.

A modified Kemmerer sampler, Figure 6.2-2, is often used for sampling surface water as well as ground water. Figure 6.2-3 shows a standard bailer with bottom check valve.

- o Advantages of Bailers:

  - Can be constructed from a wide variety of materials
  - Economical and convenient enough so that a separate bailer may be dedicated to each well; some bailers are disposable
  - No external power source required

- Reduces outgassing of volatile organics

o Disadvantages of Bailers:

- Impractical for purging large volumes of stagnant water from a well

- Transfer of water sample from bailer to sample bottle can result in aeration

-Cross-contamination may occur if equipment is not adequately cleaned after eac

<u>6.2-3.2 Submersible Pumps</u>

Submersible pumps are generally acceptable for all sampling activities except VOA sample collection. The reason for this is that submersible pumps may introduce air into the sample causing the volitilization and loss of the constituents being tested for. They are most often used for well purging and, therefore, may be utilized for sampling immediately after purging.

Other than bailing for VOA, submersible pumps are considered one of the most efficient means of sampling moderately deep (50-150') wells. They are difficult to transport, but accomplish sampling more quickly than bailers or peristaltic pumps and have variable flow rates (high for purging; low for sampling). Submersible pumps are not recommended for highly turbid waters due to rotor-binding problems.

o Advantages:

- Can be used to sample or purge several monitoring wells in a brief period of time
- Dependent upon size of pump and pumping depths, relatively large pumping rates are possible
- Can be dedicated to a single well if desired

o Disadvantages:

- Submersible pumps currently available require a minimum well casing inside diameter of two inches
- Require relatively large amount of support equipment service
- Not suitable for sampling organics
- Must be decontaminated if used for more than one well

<u>6.2-3.3 Peristaltic Pumps</u>

Peristaltic pumps may be used for sampling of all analytes except VOA sample analysis. Their use is limited to vertical lifts of about 20 feet. These pumps never contact the sample, so decontamination is not an issue as new tubing is utilized instead. This aspect is especially appealing for shallow, highly contaminated ground water sampling. Transportation is relatively easy and flow may be regulated. Turbid waters will not affect pump operation.

6.2-3.4 Bladder Pumps

Bladder pumps for environmental sampling are available with silicone or teflon bladders. These pumps require a source of compressed air and, therefore, are more difficult to transport than other pumps. However, they provide lift for sampling up to 400' deep. Flow may be varied for purging or sampling by changing the cycle rate. They provide marginally better results than submersible pumps in highly turbid waters. Due to the large internal area, bladder pumps are considered more difficult to decontaminate than other pumps.

6.2-4 GROUNDWATER SAMPLING

Water sample containers are generally filled directly from the source, the sampler or the pump discharge without special considerations. A major exception is the collection of Volatile Organic Analyte (VOA) samples.

6.2-4.1 Procedures Applicable Only to Collection of Ground Water Samples for Volatile Organic Analysis

VOA samples must be collected as specified below. Each sample is taken in duplicate.

1. Uncap the sample bottle (Figure 6.2-4), taking care not to touch the teflon-faced septum (shiny side). If the septum is contaminated in any way, it should be replaced.

2. If a chlorine residual is potentially present, check for chlorine content with Potassium Iodine (KI) paper, a chlorine residual comparator, or a DPD kit. Note that KI paper will not detect low levels of residual chlorine and comparators are subject to interferences from turbidity and sample color. Thus EPA recommends using DPD kits (DPD colorimetric method).

   If a residual chlorine content is detected, add four drops of concentrated Hydrochloric Acid to the sample container prior to filling the bottle.

3. Fill the sample vial slowly from bailer or equivalent discharge point, minimizing air entrainment, until the vial overflows.

4. Place the teflon-faced silicone rubber septum on the convex meniscus, teflon side (shiny side) down, and screw cap on (see Figure 6.2-4).

5. Invert the bottle; tap lightly to check for air bubbles.

6 .If air bubbles are present, open the bottle, and add additional sample to eliminate air bubbles, then reseal and repeat STEP 5.

6.2-4.2 Procedures Applicable Only to Collection of Ground Water Samples for Metals Determination

Generally if the well is pumped ahead of time the sample should not have to be filtered. In some cases (e.g. water is very silty), field filtration of samples may be required. This should be determined in advance and communicated to the laboratory. This is an important distinction since data obtained from the analysis of filtered samples are termed "dissolved" constituents while those from non-filtered samples are termed "total".

Filtering of any sample collected for organic analysis should be avoided. Allowing the samples to settle prior to analysis followed by decanting of the liquid is the preferred technique to avoid loss of organic constituents.

When field filtering is required, an appropriate filter medium must be selected to avoid potential sample contamination during the filtering process. If the water is thought to be contaminated by organic solvents, use of filter media such as cellulose or polycarbonate must be avoided; glass fiber or teflon filters should be used. Glass fiber filters should be rinsed in acid followed by a deionized water rinse prior to use for filtering trace metal or nutrient samples. Filtration procedures are described in Table 6.3-1. In all cases, the laboratory should be advised if samples have been filtered in the field. A general outline of the sampling procedure is as follows, refer to Section 6.3 for additional information.

1. Fill the sample container from sampling device or equivalent discharge point.

2. Add sufficient 1:1 Nitric Acid to the sample to bring the pH down to 2.0 for sample preservation.

6.2-4.3 Procedures for Collection of Ground Water Samples

General procedures for collecting groundwater samples are described below. See Section 6.3 for more specific instructions.

1. After purging, lower the sampling device to the middle of the screened interval or mid-point of the static water level. If the analysis to be performed is for lighter-than-water chemical species, then the sampling device should be lowered to the top of the water column for sample collection.

2. Collect the sample(s). Volatile and semivolatile samples are filled directly from a bailer with as little agitation as possible.

   Other samples should be placed directly into the appropriate container from the bailer or pump discharge.

3. Remove the pump or bailer from the well and, if necessary, decontaminate the pump, tubing or bailer by flushing with decontamination fluid specified in the site-specific quality assurance specifications. Preferably, field decontamination should be avoided. Otherwise, extreme caution must be exercised to avoid introducing contamination. Up to one pint of solvent is used as needed. Rinse the bailer with one gallon of potable or deionized water. Rinse again with deionized water.

4. Do <u>not</u> use deionized water stored in plastic (polyethylene) containers for field use as the deionized water will leach phthalates from polyethylene storage containers and may actually introduce contamination if used for on-site equipment clean up. Nalgene, glass, or Teflon bottles should be used.

5. Complete sample Data Record (see Figure 6.2-5) after each well is sampled.

6. Secure the well cap and lock.

7. Place samples in a cool place (4^{o} C) immediately for transport to laboratory.

REFERENCES

EPA, 1982, Handbook for sampling and sample preservation of water and wastewater: Cincinnati, OH, EPA-600/4-82-029, 402 p.

SECTION 6.2
SAMPLING TECHNIQUES

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FIELD INSTRUMENTION & MATERIAL QUALITY ASSURANCE RECORD

PROJECT ______ JOB NUMBER ______ DATE ______

FIELD INSTRUMENTATION CALIBRATION DATA

EQUIP. TYPE/I.D.	BATTERY CONDITION	CALIBRATION INFORMATION
______	______	pH 4 ______ pH 7 ______ pH 10 ______
______	______	pH 4 ______ pH 7 ______ pH 10 ______
______	______	pH 4 ______ pH 7 ______ pH 10 ______
______	______	COND STD. ______/______ COND STD. ______/______
______	______	COND STD. ______/______ COND STD. ______/______
______	______	COND STD. ______/______ COND STD. ______/______
DISSOLVED OXYGEN		
______	______	AVG. WINKLER VALUE ______PPM METER VALUE______PPM
REDOX		
______	______	ZOBELL SOL. VALUE ______ METER VALUE ______
PHOTOIONIZATION METER		
______	______	ZERO/ZERO AIR? [ ] YES [ ] NO SPAN GAS VALUE ______PPM EQUIV. METER VALUE ______PPM EQUIV.
______	______	ZERO/ZERO AIR? [ ] YES [ ] NO SPAN GAS VALUE ______PPM EQUIV. METER VALUE ______PPM EQUIV.
OTHER		
______	______	______

FLUIDS/MATERIALS RECORD

DEIONIZED WATER SOURCE: [ ] LAB [ ]PORTABLE SYSTEM [ ] OTHER ______

TRIP BLANK WATER SOURCE: [ ] LAB, LOT NO. ______

[ ] OTHER, TYPE ______ ID ______

DECONTAMINATION FLUIDS: [ ] METHYL HYDRATE; LOT NO. ______

[ ] OTHER, TYPE ______ ID ______

HNO3/DI RINSE SOLUTION: [ ] LAB , LOT NO. ______

FILTRATION PAPER ID: (IN LINE) MANUF/TYPE ______ LOT NO. ______/______

(VACUUM) MANUF/TYPE ______ LOT NO. ______

CHEMICALS USED: [ ] HNO3 LOT NO. ______ ZnAOC LOT NO. ______

[ ] H2SO4 LOT NO. ______ OTHER LOT NO. ______

[ ] HCL LOT NO. ______ OTHER LOT NO. ______

[ ] NaOH LOT NO. ______

SAMPLER SIGNATURE ______

Source: ABB-ES

Figure 6.2-1

Field Instrumentation Quality Assurance Record.

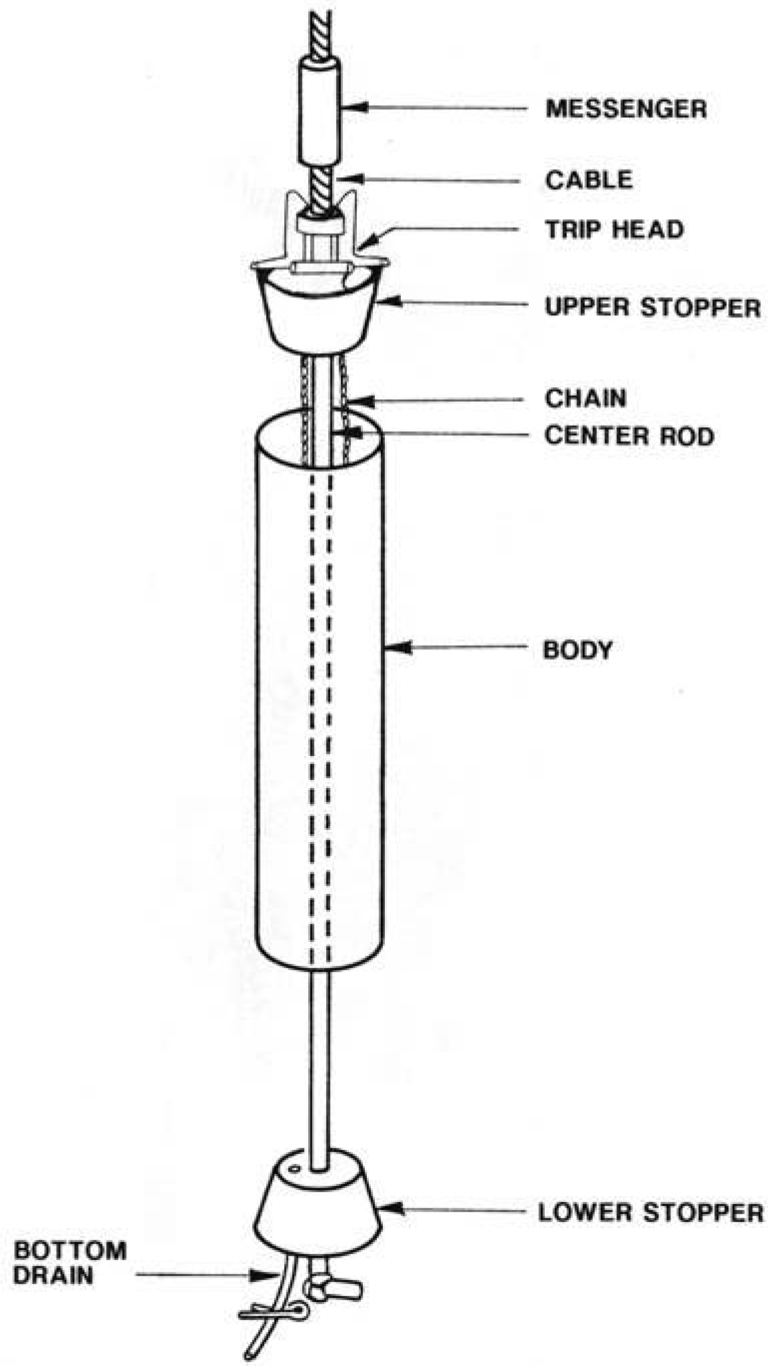
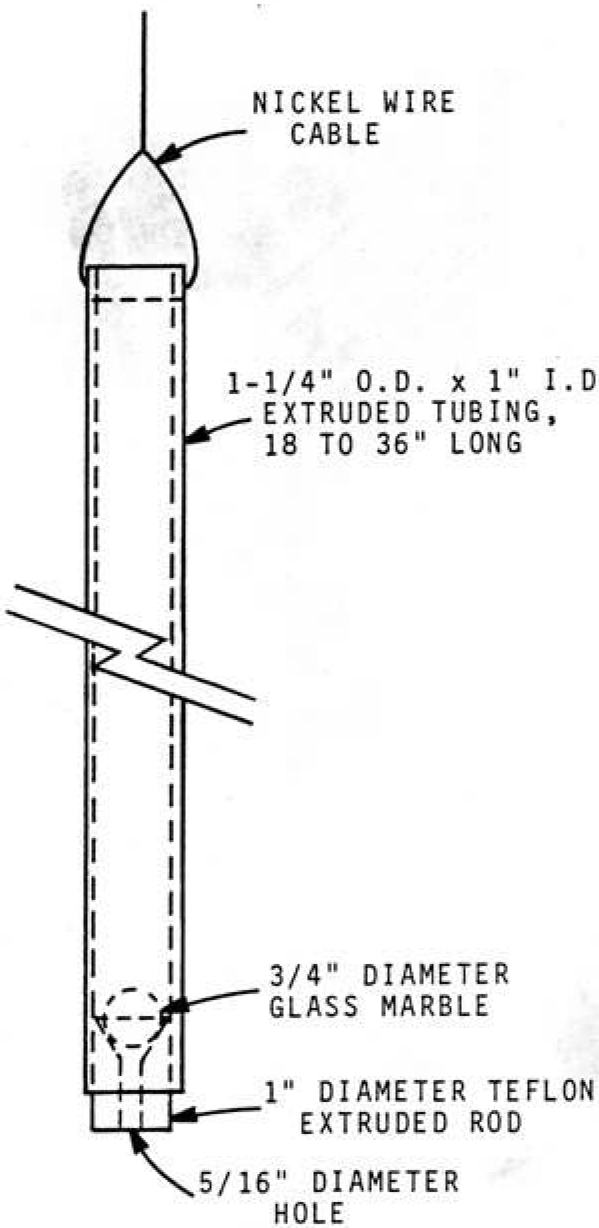


Figure 6.2-2

Source: EPA (1982)

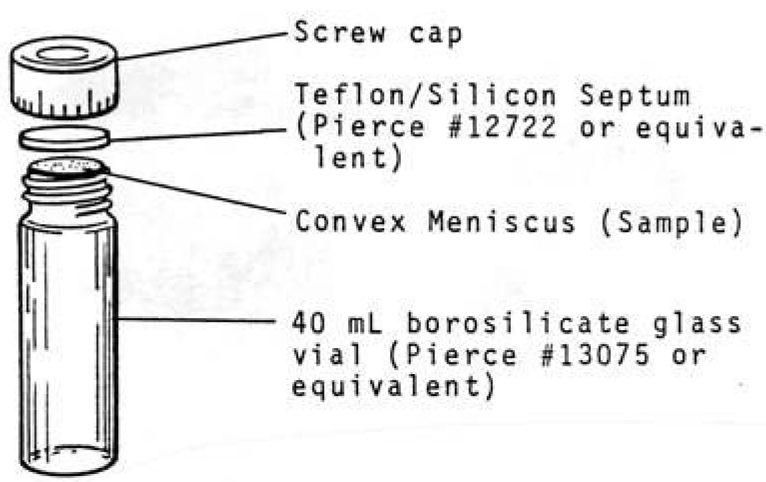
Modified Kemmerer Sampler.



Source: EPA (1982)

Figure 6.2-3

Teflon or Stainless Steel Bailer.



Source: EPA (1982)

Figure 6.2-4

Volatile Organic Collection Bottle.

PAGE ____ OF ____

PROJECT [ ] JOB NUMBER [ ] DATE [ ]

SAMPLE LOCATION ID [ ] LOCATION ACTIVITY START: END:

WATER LEVEL / WELL DATA

WELL DEPTH ____ FT [ ]MEASURED [ ]HISTORICAL [ ] TOP OF WELL [ ] TOP OF PROT. CASING [ ] ____ CASING STICK-UP (FROM GROUND) ____ FT CASING/WELL DIFF. ____ FT

WATER DEPTH ____ FT

WELL MATERIAL: [ ] PVC [ ]____ [ ] SS

WELL LOCKED?: [ ] YES [ ] NO

WELL DIA. [ ] 2 INCH [ ] 4 INCH [ ] 6 INCH [ ]____

WATER LEVEL EQUIP. USED: [ ] ELECT.COND.PROBE [ ] FLOAT ACTIVATED [ ] PRESS. TRANSDUCER [ ] ____

HEIGHT OF WATER COLUMN ____ FT X [ ] .16 GAL/FT (2 IN.) [ ] .65 GAL/FT (4 IN.) [ ] 1.5 GAL/FT (6 IN.) [ ] ____GAL/FT (____IN.) = ____ GAL/VOL ____ TOTAL GAL PURGED

WELL INTEGRITY: YES NO
PROT. CASING SECURE [ ] [ ]
CONCRETE COLLAR INTACT [ ] [ ]
OTHER ____

EQUIPMENT DOCUMENTATION

PURGING/SAMPLING EQUIP. USED: √ IF USED FOR: PURGING SAMPLING

PURGING	SAMPLING	EQUIPMENT	EQUIPMENT ID
[ ]	[ ]	PERISTALTIC PUMP	____
[ ]	[ ]	SUBMERSIBLE PUMP	____
[ ]	[ ]	BAILER	____
[ ]	[ ]	PVC/SILICON TUBING	
[ ]	[ ]	TEFLON/SILICON TUBING	
[ ]	[ ]	AIR LIFT	
[ ]	[ ]	HAND PUMP	____
	[ ]	IN-LINE FILTER	
	[ ]	PRESS/VAC FILTER	
[ ]	[ ]	____	____

DECONTAMINATION FLUIDS USED: (√ ALL THAT APPLY AT LOCATION)
[ ] ETHYL ALCOHOL
[ ] DEIONIZED WATER
[ ] TSP SOLUTION
[ ] HEXANE
[ ] HNO3/D.I.WATER SOLUTION
[ ] POTABLE WATER
[ ] NONE
[ ] ____
[ ] ____

FIELD ANALYSIS DATA

AMBIENT AIR VOA ____ PPM WELL MOUTH ____ PPM FIELD DATA COLLECTED [ ]IN-LINE [ ]IN CONTAINER

PURGE DATA	@ ____ GAL	@ ____ GAL	@ ____ GAL	@ ____ GAL	@ ____ GAL
TEMPERATURE, DEG C					
pH, units					
SPECIFIC CONDUCTIVITY (umhos/cm. @ 25 deg.c)					
OXIDATION-REDUCTION,+/- mv					
DISSOLVED OXYGEN, ppm					

SAMPLE OBSERVATIONS:
[ ] TURBID
[ ] COLORED
[ ] CLOUDY
[ ] CLEAR
[ ] ODOR

SAMPLE COLLECTION REQUIREMENTS
(√ IF REQUIRED AT THIS LOCATION)

ANALYTICAL PARAMETER	√ IF FIELD FILTERED	PRESERVATION METHOD	VOLUME REQUIRED	√ IF SAMPLE COLLECTED	SAMPLE BOTTLE ID'S
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____
[ ]				[ ]	____/____/____/____

NOTES:

SIGNATURE OF SAMPLER ____

Source: ABB-ES

Figure 6.2-5

Sample Data Record.

SECTION 6.3
SAMPLE HANDLING

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6.3 SAMPLE HANDLING

6.3-1 FILTRATION

In some cases, field filtration of samples may be required. This should be determined in advance and communicated to the laboratory. This is an important distinction since data obtained from the analysis of filtered samples are termed "dissolved" constituents while those from non-filtered samples are termed "total". In the case of metals, another option is the collection of an unfiltered sample followed by a milder digestion than that used in the total metals determination; results from this analysis are termed "total recoverable metals".

Filtering of any sample collected for organic analysis should be avoided. Allowing the samples to settle prior to analysis followed by decanting of the liquid is the preferred technique to avoid loss of organic constituents.

When field filtering is required, an appropriate filter medium must be selected to avoid potential sample contamination during the filtering process. If the water is thought to be contaminated by organic solvents, use of filter media such as cellulose or polycarbonate must be avoided; glass fiber or teflon filters should be used. Glass fiber filters should be rinsed in acid followed by a deionized water rinse prior to use for filtering trace metal or nutrient samples. Filtration procedures are described in Table 6.3-1.

A typical sample splitting flow chart is shown in Figure 6.3-1.

6.3-2 HOLDING TIMES AND PRESERVATION

Sample holding times are specified for the initiation of chemical analyses, usually beginning at the time of sample collection but occasionally (e.g., EPA's Contract Laboratory Program) beginning at the time of sample receipt at the laboratory. This determination must be made prior to sampling to allow proper logistical planning for sample shipments. Holding times also vary with the regulatory basis under which analyses are conducted. It is essential that the laboratory be consulted before sampling takes place in order to properly schedule the work. This will ensure that the laboratory will have a staff member available to receive the samples and that the laboratory can analyze the sample within the appropriate holding time.

Unless the proper sample bottle preparation and sample preservation measures are taken in the field, sample composition can be altered by contamination, degradation, biological transformation, chemical interactions, and other factors during the time between sample collection and analysis. Steps taken to maintain the in-situ characteristics required for analysis may include refrigeration of samples at 4°C, freezing, pH adjustment, and chemical fixation. Samples are preserved according to the protocol established for the specific analytical method and for specific regulatory requirements selected to obtain the desired data. These requirements are established on a case-by-case basis.

Holding times and preservation requirements for several analytes under different regulatory bases are presented in Tables 6.3-2, 6.3-3, 6.3-4 and 6.3-5.

6.3-3 SHIPPING

Sample containers are generally packed in picnic coolers for shipment. Bottles are to be packed tightly so that no motion is possible. Styrofoam, vermiculite, and "bubble pack" are suitable for most instances. Some materials that are considered to be highly hazardous require special preparation, containerization and labeling. Department of Transportation (DOT) guidelines and regulations should be consulted prior to shipment of any materials considered to be hazardous. Ice is placed in double "Ziploc" bags and added to the cooler along with all paperwork in a separate "Ziploc" bag. Sealed containers of heat transfer fluids (e.g., "Blue Ice") may also be used. Solid carbon dioxide (dry ice) is not an acceptable alternative. The cooler top is then taped shut. Custody seals and taping of coolers are generally required.

The standard procedure followed for shipping environmental samples to the analytical laboratory is, as follows:

1. All shipping of environmental samples collected must be done through overnight delivery service.

   Note: Samples <u>must not</u> be shipped unless:

   (a) next-day arrival is quarantined by the delivery service, and

   (b) the receiving laboratory has agreed to be open to receive them.

2. Prior to leaving for the field, the task leader responsible for sample collection must notify the laboratory manager of the number, type and approximate collection and shipment dates for the samples. If the number, type or date of shipment changes due to site constraints or program changes, the task leader must notify the laboratory of the changes. This notification from the field also needs to occur when sample shipments will arrive on Saturdays.

3. If prompt shipping and laboratory receipt of the samples cannot be guaranteed (i.e., Sunday arrival), the task leader will be responsible for proper storage of the samples until adequate transportation arrangements can be made. Proper storage requires that the samples be refrigerated, and in some cases, locked in a secure location. Storing samples in one's car or leaving them in the office are <u>not</u> acceptable procedures.

4. The laboratory should be notified if advance if parameters such as BOD or holding times <48 hrs are included in the shipment.

These communications are necessary to allow the laboratory enough time to prepare for the samples' arrival.

The samples are shipped to the laboratory together with the Chain of Custody (COC) documents described in Section 6.4 and an applicable Analytical Request Form (see example Figure 6.3-2).

6.3-4 TRACKING

Figure 6.3-3 is an example of a sample tracking form. Tracking of samples should commence at the time of sample container label generation. A site-specific database of anticipated sample collection should be created, then updated as analytical request forms and chain-of-custody forms are received from the field. This database can be hand-scribed, but tracking of data is better done in a computerized format, that is able to sort through and organize the data according to different parameters.

A letter of receipt from the laboratory provides the information to verify the following:

- o analytical program
- o turn-around time
- o laboratory internal identification numbers
- o chain-of-custody for shipped samples

REFERENCES

Guidelines Establishing Test Procedures for the Analysis of Pollutants Under the Clean Water Act (Federal), 40 CFR Part 136.

RCRA Groundwater Monitoring Technical Enforcement Guidance Document, US EPA, Office of Waste Programs Enforcement (OSWER), Sept 1986.

Test Methods for Evaluating Solid Waste, Physical/ Chemical Methods, 3rd Edition, Proposed Update Package, "SW-846", Dec 1987.

User Guide to the Contract Laboratory Program, EPA, Office of Environmental Response and Remediation (OERR)/Contract Laboratory Program (CLP), Dec 1988.

SECTION 6.3
SAMPLE HANDLING

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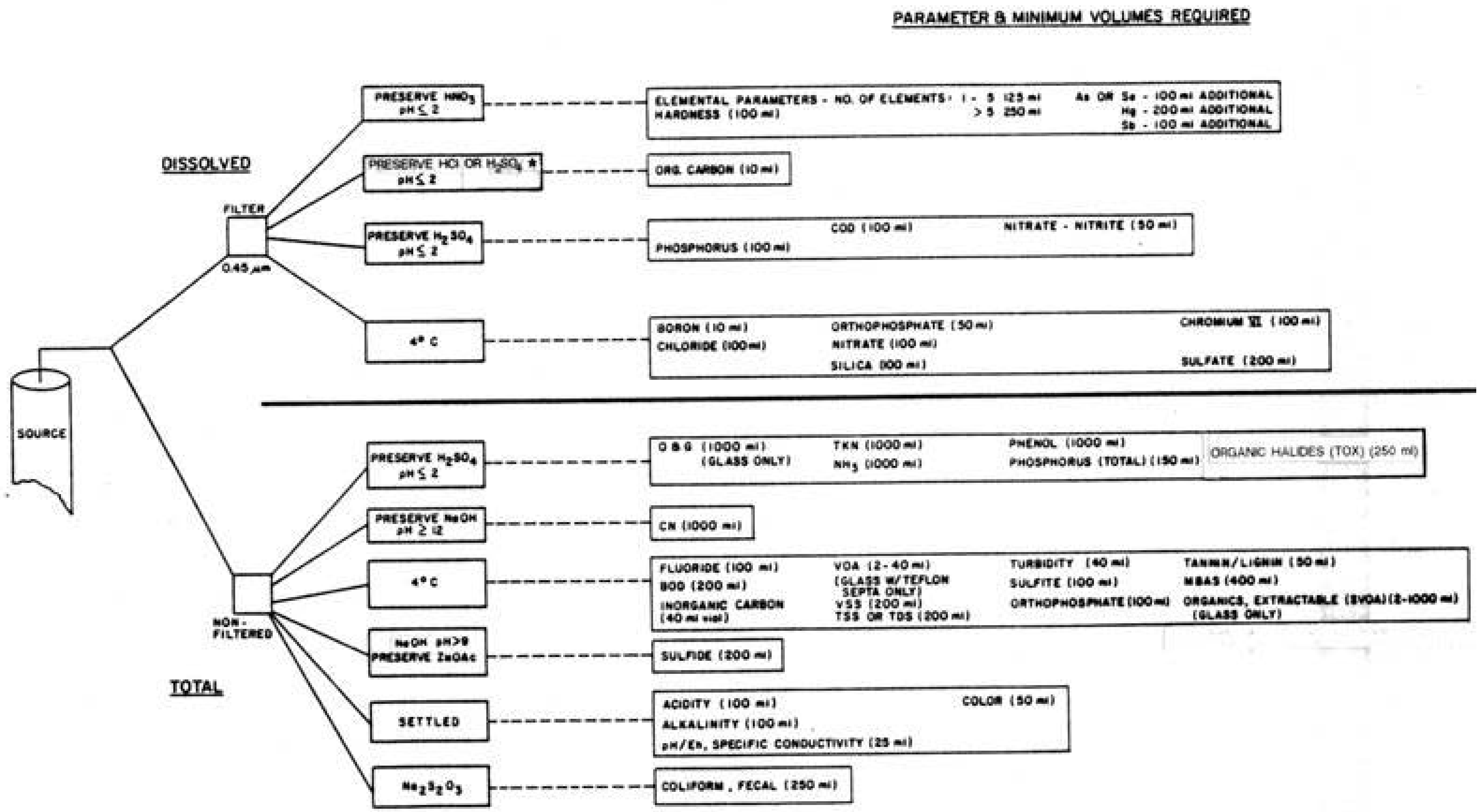
SAMPLE SPLITTING FLOW CHART–GROUNDWATER/SURFACE WATER MONITORING



★ Preservative (HCl or H_2SO_4) depends upon instrument manufacturer's directions - consult with lab.

NOTE: ALL SAMPLES SHOULD BE KEPT AT 4°C REGARDLESS OF PRESERVATIVE

Source: ABB-ES

Figure 6.3-1

Sample Splitting Flow Chart.

CLIENT INFORMATION: NAME ____________

COMPANY ____________

MAILING ADDRESS ____________

____

JOB NUMBER ____________

ANALYSES REQUESTED BY: ____________
TECHNICAL PROJECT PROFESSIONAL

APPROVED BY: ____________
PROJECT MANAGER

SAMPLE IDENTIFICATION	LAB NUMBERS	DATE SAMP'D	SAMP'D BY	ANALYSES REQUIRED

DATE RECEIVED ____________
LAB LOCATION ____________
RESULTS DUE ____________
CLIENT I.D. NO. ____________
☐ SOLID WASTE DATA FILE
☐ DATA DOCUMENTATION REQ'D
☐ ENTERED IN COMPUTER

TYPE OF SAMPLE ____________
LIST ANY HAZARDS ____________

☐ SPECIAL PROCEDURE

ADDITIONAL INFORMATION OR SPECIAL PROCEDURES ____________

Source: ABB-ES

Figure 6.3-2

Sample Analytical Request Form.

Page: Date:

Project:

Job Number:

Sample ID	Lab Number	Matrix	Analysis	Date Sampled	Hardcopy Received	Box Number	File Name	A	V	S	Final Table	Comments
01SD115xxx01xx	8253-026	Sediment	CLP-COP	9/08/88	11/16/88	4607-B05-A	BR18	X				
01SD118xxx01xx	8256-021	Sediment	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR08	X				MS/MSD
01SD118xxx01xx	8256-021	Sediment	CLP-COP	9/09/88	11/16/88	4607-B05-A	BR18	X				MS/MSD
01SD119xxx01xx	8256-022	Sediment	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR08	X				
01SD119xxx01xx	8256-022	Sediment	CLP-COP	9/09/88	11/16/88	4607-B05-A	BR18	X				
01SD303xxx01xx	8252-030	Sediment	CLP-CIP	9/07/88	11/04/88	4607-B03-B	BR08	X				
01SD303xxx01xx	8252-030	Sediment	CLP-COP	9/07/88	10/31/88	4607-B03-A	BR05	X	X	X		
01SD304xxx01xx	8252-031	Sediment	CLP-CIP	9/07/88	11/04/88	4607-B03-B	BR08	X				
01SD304xxx01xx	8252-031	Sediment	CLP-COP	9/07/88	10/31/88	4607-B03-A	BR05	X	X	X		
01SD305xxx01xx	8252-032	Sediment	CLP-CIP	9/07/88	11/04/88	4607-B03-B	BR08	X				
01SD305xxx01xx	8252-032	Sediment	CLP-COP	9/07/88	10/31/88	4607-B03-A	BR05	X	X	X		
01SD918xxx01xx	8267-003	Sediment	CLP-CIP	9/22/88	11/08/88	4607-B04-B	BR16	X				
01SD918xxx01xx	8267-003	Sediment	CLP-COP	9/22/88	11/17/88	4607-B05-C	BR21	X				No VOA
01SS118xxx01xx	8253-029	Soil	CLP-CIP	9/08/88	11/04/88	4607-B03-B	BR08	X				
01SS118xxx01xx	8253-029	Soil	CLP-COP	9/08/88	11/16/88	4607-B05-A	BR18	X				
01SW004xxx01xx	8253-012	Water	CLP-CIP	9/08/88	11/04/88	4607-B03-B	BR06	X				
01SW004xxx01xx	8253-012	Water	CLP-COP	9/08/88	11/09/88	4607-B04-C	BR11	X				
01SW113xxx01Dx	8256-014	Water	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR06	X				
01SW113xxx01Dx	8256-014	Water	CLP-COP	9/09/88	11/01/88	4607-B04-D	BR13	X				
01SW113xxx01xx	8256-013	Water	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR06	X				
01SW113xxx01xx	8256-013	Water	CLP-COP	9/09/88	11/01/88	4607-B04-D	BR13	X				
01SW114xxx01xx	8256-015	Water	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR06	X				
01SW114xxx01xx	8256-015	Water	CLP-COP	9/09/88	11/01/88	4607-B04-D	BR13	X				
01SW115xxx01xx	8253-017	Water	CLP-CIP	9/08/88	11/04/88	4607-B03-B	BR06	X				
01SW115xxx01xx	8253-017	Water	CLP-COP	9/08/88	11/09/88	4607-B04-C	BR11	X				
01SW118xxx01xx	8256-016	Water	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR06	X				MS/MSD
01SW118xxx01xx	8256-016	Water	CLP-COP	9/09/88	11/01/88	4607-B04-D	BR13	X				MS/MSD
01SW119xxx01xx	8256-017	Water	CLP-CIP	9/09/88	11/04/88	4607-B03-B	BR06	X				
01SW119xxx01xx	8256-017	Water	CLP-COP	9/09/88	11/01/88	4607-B04-D	BR13	X				
01SW918xxx01xx	8267-002	Water	CLP-CIP	9/22/88	11/08/88	4607-B04-B	BR15	X				
01SW918xxx01xx	8267-002	Water	CLP-COP	9/22/88	11/17/88	4607-B05-C	BR21	X				
01TB001xxx01xx	8252-001	Water	CLP-COP/VOA	9/06/88	10/31/88	4607-B03-A	BR04	X				
01TB002xxx01xx	8253-003	Water	CLP-COP/VOA	9/08/88	11/09/88	4607-B04-C	BR11	X				

Source: ABB-ES

Figure 6.3-3

Sample Tracking Form.

STANDARD FIELD FILTRATION PROCEDURE

(a) IN-LINE FILTRATION

Equipment

1. A portable 102-mm acrylic backflushing filter unit
2. 102-mm diameter filter papers, 0.45-μm membrane filters
3. Deionized (DI) rinse water
4. 1:1 reagent grade nitric acid rinse solution

Procedures

1. After assembling filter paper into filter holder, attach in-line filter assembly to discharge line of sampling pump. Open by-pass valve completely.
2. Turn sampling pump on, and slowly turn by-pass valve closed, allowing flow into the filter. Remove trapped air through the filter bleed valve, if necessary.
3. Rinse barrel and filter holder assembly between samples with three rinses of reagent water. The rinse sequence when elemental parameters will be analyzed is: DI water - 1:1 reagent grade nitric acid - DI water.

(b) VACUUM FILTRATION

1. Two sets of either glass funnel type or self-contained polysulfone filters with sintered glass discs or polysulfone filter plates.
2. 47-mm diameter filter papers, 0.45-μm membrane filters.
3. Vacuum pump or ISCO peristaltic pump with silicone tubing
4. DI rinse water
5. 1:1 reagent grade nitric acid rinse solution.

Procedures

1. Thoroughly rinse sintered glass disc, filter funnel, and stem polysulfone filter units with DI water.

Table 6.3-1

Standard Field Filtration Procedures.

(b) VACUUM FILTRATION (cont.)

2. On the basis of visual clarity of sample, prefiltering with larger pore filters may be required. If sample has a heavy clay content, organics, or suspended matter, prefiltration through a 3.0- or 5.0-μm membrane filter may be necessary.

3. Place membrane filter on filter holder with minimum handling.

4. Attach filter holder with filter to filter funnel and receiver.

5. Swirl and slowly pour contents of sample bottle into filter funnel.

6. Attach suction tubing to filter flask and vacuum pump (or ISCO pump). Pump is turned on in the vacuum mode.

7. Filter a small portion of the sample and discard filtrate after rinsing flask with sample filtrate.

8. If prefiltering was required, pass the sample through a 0.45-μm membrane filter using another filtering apparatus.

9. Transfer the filter sample to appropriate bottles.

10. Rinse filtration equipment between samples with at least three rinses of DI water. The rinse sequence, when elemental parameters are to be analyzed, is: DI water - 1:1 reagent grade nitric acid - DI water.

(c) PRESSURE FILTRATION

Equipment

1. Pressure filter apparatus consisting of 1-liter barrel filter, filter holder and pressure hose connectors.

2. Source of pressurized inert gas, (e.g., tank of nitrogen, argon, etc.).

3. 147-mm filter papers, 0.45-μm membrane filter.

4. DI rinse water.

5. 1:1 reagent grade nitric acid rinse solution.

Procedures

1. If filter barrel has sample valve, assemble with 0.45-μm membrane filter and attach pressure hose.

Table 6.3-1
(continued)
Standard Field Filtration Procedures.

(c) PRESSURE FILTRATION (cont.)

2. If filter barrel does not have a sample valve, assemble filter paper on filter holder.

3. Turn barrel upside down and pour sample into barrel.

4. Place filter holder and filter onto barrel assembly, making sure to align 0-ring for a positive seal.

5. Attach swing-away bolts and tighten hand-tight.

6. Turn over filter assembly and attach pressure hose assembly.

7. Slowly turn on pressurized gas and increase pressure regulator to a maximum of 20 psi.

8. Collect filtrate from bottom of barrel assembly.

9. Rinse barrel and filter holder assembly between samples with three rinses of DI water. The rinse sequence when elemental parameters will be determined is: DI water - 1:1 reagent grade nitric acid - DI water.

Table 6.3-1
(continued)
Standard Field Filtration Procedures.

Parameter	Container	Preservative	Holding Time
Volatile Organics			
Concentrated Waste Samples	8-oz. widemouth glass with Teflon liner	None	14 days
Liquid Samples			
No Residual Chlorine Present	2 40-ml vials with Teflon lined septum caps	4 drops conc. HCl, Cool, 4° C	14 days
Residual Chlorine Present	20 40-ml vials with Teflon lined septum caps	Collect sample in a 4 oz. soil VOA container which has been pre-preserved with 4 drops of 10% sodium thiosulfate. Gently mix sample and transfer to a 40-ml VOA vial that has been pre-preserved with 4 drops of conc. HCl, Cool to 4° C	14 days
Acrolein and Acrylonitrile	2 40-ml vials with Teflon lined septum	Adjust to pH 4-5, Cool, 4° C	14 days
Soil/Sediments and Sludges	4-oz. (120-ml) wide-mouth glass with Teflon liner	Cool, 4° C	14 days

Source: Proposed Update 3rd. Ed. SW-846

Table 6.3-2 (page 1 of 2)
Recommended Sample Containers, Preservation Techniques, and Holding Times for Volatiles and Semi-Volatile Organics. (SW-846, 3rd Edition)

Parameter	Container	Preservative	Holding Time
Semi-Volatile Organics/Organochlorine Pesticides/PCBs			
Concentrated Waste Samples	8-oz. widemouth glass with Teflon liner	None	Samples must be extracted within 14 days and extract analyzed within 40 days following extraction.
Water Samples			
No Residual Chlorine Present	1-gal. or 2 1/2-gal. amber glass with Teflon liner	Cool, 4^{o} C	Samples must be extracted within 7 days and extracts analyzed within 40 days following extraction.
Residual Chlorine Present	1-gal. or 2 1/2-gal. amber glass with Teflon liner	Add 3 ml 10% sodium thiosulfate per gallon, Cool, 4^{o} C	Samples must be extracted within 7 days and extracts analyzed within 40 days following extraction.
Soil/Sediments and Sludges Sludges	8-oz. widemouth glass with Teflon liner	Cool, 4^{o} C	Samples must be extracted within 14 days and extract analyzed within 40 days following extraction.

Source: Proposed Update 3rd. Ed. SW-846

Table 6.3-2
(page 2 of 2)
Recommended Sample Containers, Preservation Techniques, and Holding Times for Volatiles and Semi-Volatile Organics. (SW-846, 3rd Edition)

Name	Container[1]	Preservation	Maximum holding time
Bacterial Tests:			
Coliform, total	P, G	Cool, 4°C, 0.008% $Na_2S_2O_3$	6 hours
Inorganic Tests:			
Chloride	P, G	None required	28 days
Cyanide, total and amenable to chlorination	P, G	Cool, 4°C; if oxidizing agents present add 5 mL 0.1N $NaAsO_2$ per L or 0.06 g of ascorbic acid per L; adjust pH>12 with 50% NaOH.	14 days
Hydrogen ion (pH)	P, G	None required	Analyze immediately
Nitrate	P, G	Cool, 4°C	48 hours
Sulfate	P, G	Cool, 4°C	28 days
Sulfide	P, G	Cool, 4°C, add zinc acetate	7 days
Metals:			
Chromium VI	P, G	Cool, 4°C	24 hours
Mercury	P, G	HNO_3 to pH<2	28 days
Metals, except chromium VI and mercury	P, G	HNO_3 to pH<2	6 months
Organic Tests:			
Oil and grease	G	Cool, 4°C[2]	28 days
Organic carbon, total (TOC)	P, G	Cool, 4°C[2]	28 days
Purgeable Halocarbons	G, Teflon-lined septum	Cool, 4°C[3]	14 days
Purgeable aromatic hydrocarbons	G, Teflon-lined septum	Cool, 4°C, 0.008% $Na_2S_2O_3$[2,3]	14 days
Acrolein and acrylonitrile	G, Teflon-lined septum	Cool, 4°C, 0.008% $Na_2S_2O_3$, Adjust pH to 4-5	14 days
Phenols	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$	7 days until extraction, 40 days after extraction
Benzidines	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$	7 days until extraction, 40 days after extraction
Phthalate esters	G, Teflon-lined cap	Cool, 4°C	7 days until extraction, 40 days after extraction
Nitrosamines	G, Teflon-lined cap	Cool, 4°C, store in dark, 0.008% $Na_2S_2O_3$	7 days until extraction, 40 days after extraction
PCBs	G, Teflon-lined cap	Cool, 4°C	7 days until extraction, 40 days after extraction
Nitroaromatics and cyclic ketones	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$, store in dark	7 days until extraction, 40 days after extraction
Polynuclear aromatic hydrocarbons	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$, store in dark	7 days until extraction, 40 days after extraction
Haloethers	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$	7 days until extraction, 40 days after extraction
Chlorinated hydrocarbons	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$	7 days until extraction, 40 days after extraction
Dioxins and Furans	G, Teflon-lined cap	Cool, 4°C, 0.008% $Na_2S_2O_3$	7 days until extraction, 40 days after extraction
Total organic halides (TOX)	G, Teflon-lined cap	Cool, 4°C[2]	8 days
Pesticides	G, Teflon-lined cap	Cool, 4°C, pH 5-9	7 days until extraction, 40 days after extraction
Radiological Tests:			
Alpha, beta and radium	P, G	HNO_3 to pH<2	6 months

[1]Polyethylene (P) or Glass (G)
[2]Adjust to pH<2 with H_2SO_4, HCl or solid $NaHSO_4$
[3]Free chlorine must be removed prior to addition of HCl by exact addition of $Na_2S_2O_3$

Table 6.3-3

Source: RCRA TGED and SW-846

Required Containers Preservation Techniques, and Holding Times-Liquid Matrix Only. (RCRA TGED and SW-846)

Parameter	Container	Preservative	Holding Time	
			Soil	Water
Volatiles by gas chromatog-graphy/mass spectrometry (GC/MS)	Water - 40 mL glass vial with Teflon-lined septa Soil-Glass with Teflon-lined septa	Cool, 4°C	10 days	10 days
Polychlorinated biphenyl (PCB)/ pesticides	G, Teflon-lined lid	Cool, 4°C	Extract within 10 days, analyze 40 days	Extract within 5 days, analyze 40 days
Extractable Organics	G, Teflon-lined lid	Cool, 4°C	Extract within 10 days, analyze 40 days	Extract within 5 days, analyze 40 days
Metals	P, G	HNO_3 to pH<2	6 months	6 months
Mercury	P, G	HNO_3 to pH<2	26 days	26 days
Cyanide	P, G	NaOH to pH>12 Cool 4°C add 0.6g ascorbic acid if residual chlorine present	14 days	14 days
Chromium VI	P, G	Cool, 4°C	24 h	24 h

Note: P = polyethylene
G = glass

Source: **EPA CLP**

Table 6.3-4

Sample Containers, Preservation and Holding Requirements. (EPA's Contract Laboratory Protocal Samples)

Parameter Name	Container(1) Type	Size	Preservation(2)	Maximum Holding Time(3)
Bacterial Tests				
Coliform, fecal and total	P,G	250 mℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$	6 hours
Fecal streptococci	P,G	250 mℓ	Same as above	6 hours
Inorganic Tests				
Acidity	P,G	100 mℓ	Cool, 4°C	14 days
Alkalinity	P,G	100 mℓ	Cool, 4°C	14 days
Ammonia	P,G	1000 mℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Biochemical oxygen demand	P,G	200 mℓ	Cool, 4°C	48 hours
Bromide	P,G	100 mℓ	None required	28 days
Biochemical oxygen demand, carbonaceous	P,G	100 mℓ	Cool, 4°C	48 hours
Chemical oxygen demand	P,G	100 mℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Chloride	P,G	100 mℓ	None required	28 days
Chlorine, total residual	P,G	in field	None required	Analyze immediately
Color	P,G	50 mℓ	Cool, 4°C	48 hours
Cyanide, total and amenable to chlorination	P,G	1 ℓ	Cool, 4°C, NaOH to pH >12, 0.6g ascorbic acid	14 days
Fluoride	P	100 mℓ	None required	28 days
Hardness	P,G	100 mℓ	HNO_3 to pH <2, H_2SO_4 to pH <2	6 months
Hydrogen ion (pH)	P,G	25 mℓ	None required	Analyze immediately
Kjeldahl and organic nitrogen	P,G	1 ℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Metals				
Chromium VI	P,G	100 mℓ	Cool, 4°C	24 hours
Mercury	P,G	150 mℓ	HNO_3 to pH <2	28 days
Metals, except chromium VI and mercury	P,G	1-5 parameters-100mℓ 6-10 parameters-125mℓ >10 parameters-150mℓ	Same as above	6 months
Nonconventional Pollutants				
Nitrate	P,G	100 mℓ	Cool, 4°C	48 hours
Nitrate-nitrite	P,G	50 mℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Nitrite	P,G	100 mℓ	Cool, 4°C	48 hours
Oil and grease	G	1 ℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Organic carbon	P,G	10 mℓ	Cool, 4°C, HCl or H_2SO_4 to pH <2*	28 days
Orthophosphate	P,G	50 mℓ	Filter immediately, cool, 4°C	48 hours
Oxygen, dissolved probe	G bottle and top	in field	None required	Analyze immediately
Winkler	Same as above	200 mℓ	Fix on site and store in dark	8 hours
Phenols	G	1 ℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Phosphorus (elemental)	G	100 mℓ	Cool, 4°C	48 hours
Phosphorus, total	P,G	150 mℓ	Cool, 4°C, H_2SO_4 to pH <2	28 days
Residue, total	P,G	200 mℓ	Cool, 4°C	7 days
Residue, filterable	P,G	200 mℓ	Cool, 4°C	48 hours
Residue, nonfilterable (TSS)	P,G	200 mℓ	Cool, 4°C	7 days
Residue, settleable	P,G	1 ℓ	Cool, 4°C	48 hours
Residue, volatile	P,G	200 mℓ	Cool, 4°C	7 days
Silica	P	see metals	Cool, 4°C	28 days

* Consult with laboratory; choice of acid depends upon instrument manufacturer.

Table 6.3-5 (page 1 of 2) Sample Container, Preservation and Holding Requirements. (Clean Water Act Samples)

Parameter Name	Container(1) Type	Container(1) Size	Preservation(2)	Maximum Holding Time(3)
Specific conductance	P,G	25 mℓ	Cool, 4°C	28 days
Sulfate	P,G	250 mℓ	Cool, 4°C	28 days
Sulfide	P,G	200 mℓ	Cool, 4°C, add zinc acetate plus sodium hydroxide to pH >9	7 days
Sulfite	P,G	100 mℓ	None required	Analyze immediately
Surfactants	P,G	400 mℓ	Cool, 4°C	48 hours
Temperature	P,G	25 mℓ	None required	Analyze in field
Turbidity	P,G	40 mℓ	Cool, 4°C	48 hours
Organic Tests				
Purgeable halocarbons	G, Teflon-lined septum	40 mℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4)	14 days(5)
Purgeable aromatic hydrocarbons	Same as above	40 mℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4), HCl to pH 2	14 days(5)
Acrolein and acrylonitrile	Same as above	40 mℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4), Adjust pH to 4-5	14 days(5)
Phenols	G, Teflon-lined cap	1 ℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4)	7 days until extraction, 40 days after extraction
Benzidines	Same as above	1 ℓ	Same as above	7 days until extraction
Phthalate esters	Same as above	1 ℓ	Cool, 4°C	7 days until extraction, 40 days after extraction
Nitrosamines	Same as above	1 ℓ	Cool, 4°C, store in dark, 0.008% $Na_2S_2O_3$	Same as above
PCBs, acrylonitrile	Same as above	1 ℓ	Cool, 4°C	Same as above
Nitroaromatics and isophorone	Same as above	1 ℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4) store in dark	Same as above
Polynuclear aromatic hydrocarbons	Same as above	1 ℓ	Same as above	Same as above
Haloethers	Same as above	1 ℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4)	Same as above
Chlorinated hydrocarbons	Same as above	1 ℓ	Cool, 4°C	Same as above
TCDD	Same as above	1 ℓ	Cool, 4°C, 0.008% $Na_2S_2O_3$(4)	Same as above
Volatile Organics	G, Teflon-lined septum	40 mℓ	Cool, 4°C	14 days(5)
Semi-Volatiles	G, Teflon-lined cap	1ℓ	Cool, 4°C	7 days until extraction, 40 days after extraction
Pesticides Tests				
Pesticides	Same as above	1 ℓ	Cool, 4°C, pH 5-9	Same as above
Radiological Tests				
Alpha, beta and radium	P	1 ℓ	HNO_3 to pH <2	6 months

(1) Appropriate sample containers: P = polyethylene, G = glass.
(2) Sample preservation should be performed immediately upon sample collection. For composite chemical samples, each aliquot should be preserved at the time of collection. When use of an automated sampler makes it impossible to preserve each aliquot, then chemical samples may be preserved by maintaining at 4°C until compositing and sample splitting is completed.
(3) Samples should be analyzed as soon as possible after collection. The times listed are the maximum times that samples (preserved, as required) may be held before analyses and still be considered valid. Some samples may not be stable for the maximum time period given in the table. A permitter or monitoring laboratory is obligated to hold the sample for a shorter time if knowledge exists to show that this is necessary to maintain sample stability.
(4) Use $Na_2S_2O_3$ (sodium thiosulfate) only if chlorine is present.
(5) 7 days if unpreserved.

Source: EPA Guidelines Clean Water Act

Table 6.3-5 (page 2 of 2) Sample Container, Preservation and Holding Requirements. (Clean Water Act Samples)

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SECTION 6.4 CHAIN-OF-CUSTODY

SECTION 6.4
CHAIN-OF-CUSTODY

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6.4 CHAIN-OF-CUSTODY

6.4-1 PURPOSE

A chain-of-custody (COC) program must be followed during sample handling activities from the field through laboratory operations. This program is designed to assure that each sample is accounted for at all times. Field data sheets, COC records, and sample labels must also be completed by the appropriate sampling and laboratory personnel for each sample.

The objective of the sample custody identification and control system is to assure, to the extent practicable, that:

- all samples are uniquely identified;
- the correct samples are analyzed for the correct parameters and are traceable through their records;
- important sample characteristics are preserved;
- samples are protected from loss or damage;
- any processing of samples (e.g., filtration, preservation) is documented;
- a defensible forensic record of sample integrity is established; and
- client confidentiality is maintained.
- a sample is considered under a chain-of-custody if it meets all of the following criteria:

  (1) the sample is in your custody,

  (2) the sample is in your view, after being in your possession,

  (3) the sample is in your possession and then you locked it up to prevent tampering, and

  (4) the sample is in a designated, secured area (locked area with limited access).

6.4-2 IMPLEMENTATION

The chain-of-custody procedure begins in the field and establishes a "paper trail" so that sample possession can be traced.

The standard COC protocol used by DEP is as follows:

- o Pre-prepare labels for each sample that includes identification, date and time of collection, sample parameters to be analyzed, any preservatives added, and the name of sample collector.
- o Record the procedures and amounts of reagents or supplies necessary for each sample including sample preparation and preservation.
- o Record date and time of sampling, sampling locations, sample bottle identification, and specific sample acquisition measures on the chain-of-custody forms.
- o Complete standard field data record forms to establish sample custody in the field before sample shipment (see Section 6.3).

The COC description section requires:

- o a unique identification of each sample;
- o the name(s), address(es), and telephone number(s) of the sampler(s) and the person shipping the samples and all subsequent transfers of custody;
- o the type and method of analysis requested (sometimes this can be put on the field data sheet that accompanies the chain-of-custody form);
- o the date and time that the samples were taken and delivered for shipping; and
- o the names of those responsible for receiving the samples at the laboratory.

The COC record is used to:

- o document the identity of a sample and its handling from its first existence as a sample until analysis and data reduction are completed;
- o Custody records trace a sample from collection through all transfers of custody until it is transferred to the analytical laboratory. Internal laboratory records document the custody of the sample through its final disposition.

A typical COC record is shown in Figure 6.4-1. At least four copies of the COC must be available, 4-part NCR forms are preferred. The original and one copy must accompany the samples to the laboratory; one copy is retained by the sampling crew chief; the last copy is placed in the project file. The signed original is retained by the laboratory. Return copies of original signed by receiving laboratory to sampling crew chief and to the project file.

Where litigation is likely, custody seals must be used on sample shipments to avoid any question of tampering. In any event, routine use of custody seals is good practice.

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CHAIN OF CUSTODY

1. Case Number:________________ 3. Date of Collection:________________

2. Site Name and Location:_______ 4. Number of Samples:____________

5. Collector(s):________________

Address:________________

Telephone #:________________

Item Number	Sample Description: Field Number	Sample Description: Laboratory Number

Item No.	Relinquished By:	Received By:	Purpose of Chain-of-Custody:
	Printed Name:	Printed Name:	
	Signature: Date:	Signature: Date:	
	Printed Name:	Printed Name:	
	Signature: Date:	Signature: Date:	
	Printed Name:	Printed Name:	
	Signature: Date:	Signature: Date:	
	Printed Name:	Printed Name:	
	Signature: Date:	Signature: Date:	

Source: MADEP

Figure 6.4-1

Chain-of-Custody Record.

CHAIN OF CUSTODY

1. Case Number: 7285
3. Date of Collection: 7/2/85
2. Site Name and Location: ABC Corporation, 1000 Main Street, Boston, Massachusetts
4. Number of Samples: 10
5. Collector(s): John Doe
Address: DSHW-Northeast region
Telephone #: 617-727-5194

Item Number	Sample Description: Field Number	Sample Description: Laboratory Number
1	7285-1	R6000
2	7285-2	R6001
3	7285-3	R6002
4	7285-4	R6003
5	7285-5	R6004
6	7285-6	014001
7	7285-7	014002
8	7285-8	014003
9	7285-9	014004
10	7285-10	014005

Item No.	Relinquished By:	Received By:	Purpose of Chain-of-Custody:
1,2,3,4,5	Printed Name: John Doe Signature: John Doe Date: 7/4/89	Printed Name: Paul Smith Signature: Paul Smith Date: 7/4/89	Inorganic Analysis
1,2,3,4,5	Printed Name: Paul Smith Signature: Paul Smith Date: 7/5/89	Printed Name: Harry Jones Signature: Harry Jones Date: 7/5/89	
6,7,8,9,10	Printed Name: John Doe Signature: John Doe Date: 7/4/89	Printed Name: Carol Clark Signature: Carol Clark Date: 7/4/89	Organic Analysis
	Printed Name: Signature: Date:	Printed Name: Signature: Date:	

Source: MADEP

Figure 6.4-2

Example of a Properly Filled Out Chain-of-Custody Form.

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SECTION 6.5 DECONTAMINATION OF SAMPLING EQUIPMENT

SECTION 6.5
DECONTAMINATION OF SAMPLING EQUIPMENT

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6.5 DECONTAMINATION OF SAMPLING EQUIPMENT

6.5.1 PURPOSE

Ideally, sampling equipment, (e.g., bailers, pumps, tubing, filter holders) will be dedicated to each sampling location and precleaned in the laboratory prior to each sampling episode, thus eliminating the need for field decontamination of sampling equipment. The use of disposable sampling equipment is more expensive but totally contaminant free. When this is not possible, field decontamination of such equipment must occur prior to collection of each set of samples.

Decontamination of reusable equipment used to collect samples is essential in order to maintain chemical data integrity between sampling locations. In general, decontamination should allow for adequate cleaning of the drilling and sampling tools for the contaminants found at any given site. Different chemicals or mixtures of chemicals will require the use of different cleaning methods or compounds.

6.5-2 PROCEDURE

The method of choice for decontamination should be that which most fully removes site contaminants from the sampling equipment with least interference to the ultimate chemical analysis. Site and weather conditions frequently impose constraints upon the preferred method.

The general decontamination methods and compounds that can be used are as follows:

- Do not use distilled water stored in plastic bottles as the plastic contains too many contaminants. Bring deionized water in either nalgene bottles or teflon bottles from the laboratory.

- Equipment to be utilized in the collection of samples for metals analysis should be cleaned by the following steps:

  1. Wash equipment with a non-phosphate detergent-solution (e.g. Alconox) and a brush.

  2. Rinse thoroughly with tap water.

  3. Rinse with 1:1 nitric acid.

  4. Rinse the equipment thoroughly with deionized water (either ASTM type I or II).

  5. For water samples, rinse the equipment two to three times with the media being sampled before collecting a sample.

  6. Repeat this procedure at each location.

- o Equipment to be used for collection of samples for TPH, oil identification, and oil and grease analyses should be cleaned by the following steps:

  1. Wash equipment with a non-phosphate detergent-solution (e.g. Alconox) and a brush.

  2. Rinse with tap water.

  3. Rinse with reagent grade methanol.

  4. Rinse thoroughly with deionized water.

  5. For surface water or ground water, rinse the equipment two to three times with the media being sampled prior to collecting a sample.

  6. Repeat this at each location.

- o Equipment to be used for collection of semi-volatile organics (which include base-neutral extractables, PCBs, herbicides and pesticides) should be cleaned by the following steps:

  1. Wash equipment with a non-phosphate detergent-solution (e.g. Alconox) and a brush.

  2. Rinse with tap water.

  3. Rinse with technical grade acetone.

  4. Rinse with pesticide grade hexane.

  5. Rinse thoroughly with deionized water.

  6. For water samples, rinse the equipment two to three times with the media being sampled before collecting the sample.

  7. Repeat this procedure at each sampling location.

- o Equipment used for collection of samples for volatile organics analysis should be cleaned by the following steps:

  1. Wash equipment with a non-phosphate detergent solution (e.g. Alconox) and a brush.

  2. Rinse with tap water.

3. Rinse with reagent grade methanol.

4. Rinse thoroughly with deionized water.

5. For water samples, rinse the equipment two to three times with the media being sampled before collecting a sample.

6. Repeat this procedure at each location.

- o Steam cleaning is another acceptable technique for field decontamination.

The source of rinse water is often from nearby public sources. This should be noted and a sample collected as described in Section 6.1-3.3.

More than one method or compound may be used in series for a particular site. In extreme cases, disposable equipment is recommended over decontamination. This is because the level of effort and costs required to adequately clean the equipment and dispose of the cleaning solutions may not be warranted.

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SECTION 7.0 GROUNDWATER MODELING

SECTION 7.0
GROUNDWATER MODELING

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7.1 GROUNDWATER MODELING OVERVIEW

7.1-1 Introduction

Groundwater flow/solute transport models are tools designed to provide the user with greater understanding of, and the ability to quantify, groundwater flow and solute transport in an aquifer system. Groundwater models have been used for many years to simulate groundwater flow and are the basis for predicting solute transport in aquifers. The goal of groundwater modeling is to integrate the existing knowledge about an aquifer system such that it tests the conceptual model of the system (i.e., hypothesis testing). This is accomplished by predicting the value of an unknown variable (e.g., piezometric head or solute concentration at various points in an aquifer) given a specified set of initial and boundary conditions. Models are also used to determine flow to wells, flow to and from streams, heat transport in groundwater, regional flow patterns, flownet analyses, and production well design (Walton, 1985).

Mathematical models have gained wide acceptance in the groundwater field. This Standard Reference describes the basic differences between analytical and numerical models, outlines the principal steps in the construction of numerical groundwater flow and solute transport models, and provides recommended quality control procedures for modeling.

This section of the Standard References has been prepared in response to numerous requests for inclusion of some material about groundwater modeling. It represents an attempt by DEP to provide an overview of the subject. It does not represent an endorsement by DEP of any particular type of approach, but will discuss the appropriateness of using (or not using) a numerical rather than an analytical model in reports submitted to the department. It is outside the scope of this section to undertake an in-depth discussion of modeling techniques. Good documentation is a critical and often overlooked element in modeling. It is essential that, throughout the entire process, the modeler documents all steps performed, from the initial conceptual model through the various simulations to the final product.

7.1-2 Purpose

The purpose of a groundwater flow model is to be able to make predictions or gain insight into an aquifer system by creating, via mathematical expressions and equations, a simulation of the distribution of piezometric head in an aquifer. This simulated data set of piezometric heads represents values that have been measured at specific locations (i.e., monitoring wells, piezometers, staff gages). Once a model has been created and properly calibrated (i.e., a process of comparing simulated vs. measured heads and adjusting the model parameters accordingly), the model can be used to forecast what the distribution of head might be for a different set of pumping, recharge or aquifer conditions.

7.1.3 General Applications

There are many applications for groundwater flow models. It might be important, for example, to know what the resulting water table might look like if a cutoff wall or french drain were installed in the aquifer, or what the influence of a lagoon or impoundment would have on the flow field, or what the capture zone of a recovery well might be for different pumping rates. Larger scale applications include defining a well head protection area for a municipal water supply or predicting the geometry of a contaminant plume.
One word of caution is offered to the reader: models do not necessarily provide unique solutions when groundwater flow or contaminant transport are being modeled, since combinations of different hydrogeologic and contaminant transport parameters can produce similar results. Groundwater modeling is not an easy task. At a minimum, an in-depth understanding of groundwater flow is required. A reliable model begins with collection of comprehensive data on the aquifer being studied and ends with calibration to a wide distribution of known heads. Care must be taken not to misuse models, which may lead to erroneous conclusions. Misuse of models is more likely to occur if the data base on the aquifer is limited and does not contain significant information with which to compare and verify the response of the model.

In addition, on a larger site, as new field data is acquired, the model can be periodically updated. Thus a "second", or even "third", generation model may be constructed as more monitoring wells are installed, or as the boundary conditions are better understood, or as more water quality information is gathered.

7.2 MODELING TERMINOLOGY

7.2-1 Terminology

There are a few basic terms that must be understood in order to discuss groundwater models:

Advection - Advection is the transport of a non-reactive or conservative solute (i.e., a solute that travels without undergoing reactions with the aquifer matrix) at the average groundwater velocity that is equal, in a homogeneous porous media, to the specific discharge (q) divided by the porosity (n).

Boundary Conditions - Boundary conditions are site-specific physical or hydraulic conditions that describe the flux or piezometric head conditions at the edges of the groundwater system. Physical boundaries are formed by the presence of an impermeable body of rock or significantly lower permeability unit or large body of water while hydraulic boundaries include groundwater divides and streamlines. These boundaries, described as mathematical expressions in the model, have a dominant effect on defining groundwater flow in the aquifer being modeled. Poorly defined boundary conditions will result in a problem that is ill defined and for which no meaningful solution can be obtained. There are three basic types of boundary conditions that are used in constructing numerical flow models:

1. Specified head - The piezometric head is known for surfaces bounding the flow region. Examples include ponds, streams and reservoirs with an unchanging head that is in good hydraulic connection with the aquifer or an equipotential line of known value. As constant heads represent potentially infinite sources or sinks in the model, specification of such boundaries needs to be undertaken with care.

2. Specified flux - The flow rate (i.e., flux) is known across surfaces bounding the region. A leaky till/stratified drift boundary is an example of a specified-flow boundary. A special type of specified flux boundary is a no-flow boundary (an impervious or barrier boundary). Another example of a no-flow boundary is a groundwater divide or a flow line.

   Note: Equipotential lines or flow lines may be used as model boundaries as long as they are far enough away from nodes where pumping or recharging centers are located so that the boundaries are not influenced by these stresses.

3. Head-dependent flux - The flux is a function of head at this boundary. This is referred to as a mixed boundary because it relates boundary flux to boundary head. Its most common use is to represent interaction between a water table aquifer and a stream or river that is separated from the aquifer by a semi-pervious boundary (e.g., a silt bed lining the bottom of a channel).

Dispersion - Dispersion is the process of solute spreading and dilution as advection carries it along. It is the result of mechanical mixing as well as molecular diffusion that occurs as water migrates through a porous medium. In more permeable formation (i.e., sands and gravel) mechanical mixing and advection are the dominant processes by which a solute spreads from a source area. In low permeability formations such as clay or silty clay, molecular diffusion is generally the dominant process by which a solute migrates from a source area. It should be noted that if preferential migration pathways are present in the low permeability material, due to localized lithologic variations or the presence of vertical cracks, then advection and mechanicla mixing can play a dominant role as well.

Initial Conditions - Initial conditions are those conditions that exist in the aquifer at time equals zero in the simulation. For example, the elevation of the water table or piezometric head is often specified as an initial condition in transient groundwater flow models or initial concentrations would be specified in the case of a transient solute transport mode. In steady state simulations, the initial conditions may be relatively unimportant, but for transient simulations, the initial conditions are critical.

Model Calibration - Model calibration is the process of comparing computed values (e.g., piezometric head, stream base flow, etc.) that are determined at the end of a model run with actual values of head (i.e., measured in the field) and making adjustments to the nodal parameters or model boundary conditions until there is agreement between the two values. This is not a node-by-node exercise, but generally parameter values are varied over areas of the model to improve overall matching. While heads should match reasonably well, flow directions, hydraulic gradients and overall water balances may be even more important aspects of the calibration matching.

Model Construction - Model construction is the process of using the physical and hydrogeologic data obtained about the aquifer together with the modeler's conceptual model of the system and, by means of employing a model grid, assigning values such as hydraulic conductivity, transmissivity and storativity to each node. The boundary conditions and initial conditions are also specified during model construction as required by the conceptual model.

Model Grid - The model grid is a two or three-dimensional representation of the aquifer geometry. The model grid consists of connected quadrilaterals or triangles that resemble a screen mesh. Figure 7-1 depicts an aquifer and examples of what some two dimensional model grids might look like for finite difference or finite element model applications.

Model Simulation - A model simulation refers to the computer generating a set of piezometric heads.

Model Verification - Model verification is performed once the model is calibrated. The procedure for verifying a model is accomplished by running the model for a different set of conditions, and correspondingly a different set of measured heads, than the set that was used to calibrate the model. If the model is able to compute a set of heads for the second set of conditions that matches the field measured heads for those conditions, then the model is considered to be "verified" and "well calibrated". Care should still be exercised, however, when running the model under conditions much different than observed or calibrated.

Node - A node represents the physical position in the aquifer where the average hydrogeologic properties are defined and piezometric heads are calculated. In some models, the nodes are the centers of the grids (see Figure 7-1(b)) while in others they are the intersections of the grids (see Figure 7-1(c) and (d)). In a block centered grid, aquifer properties and hydraulic stresses are typically assigned to the block surrounding the node. In a mesh centered grid, properties are assigned to the area surrounding the node. Infinite element models, aquifer properties can either be assigned to the node or the element (Anderson and Woessner, 1992). The head at the node represents the average head for the area immediately adjacent to the node.

Solute Transport - Solute transport in groundwater is the migration of compounds in solution through a saturated, porous medium. Processes such as advection and dispersion are two of the dominant mechanisms that govern this process. A contaminant may be subject to other mechanisms such as retardation, chemical or biologic transformation, or volatilization that will reduce anticipated concentrations. A solute that does not degrade is said to be conservative.

Steady State - Steady state refers to an equilibrium condition whereby over long periods of time, hydrogeologic systems may achieve or approximate some non-changing conditions in which heads or concentrations do not change with further passage of time. Such systems are said to have achieved steady state. Models may deal with this in different ways. Some have "steady state" options, while others require the user to specify some long period of time and/or closure criterion beyond which changes in head are considered inconsequential.

Transient - Transient refers to a non-equilibrium condition whereby a model is allowed to run for a specified period of simulated time. Typically, initial conditions are steady state in order to correctly interpret head changes under transient conditions, due to stresses in the model, e.g., pumping.

7.3 MATHEMATICAL MODELS

While the earlier subsections of Section 7.3 are written primarily referencing flow modeling, the techniques and concepts apply equally to solute transport models. Section 7.3-4 discusses added considerations specific to solute transport.

7.3-1 Types of Models

A mathematical model is a set of equations that describes the physics of a system or process. Mathematical groundwater flow models are powerful tools for studying cause-and-effect relationships within groundwater systems. However, unlike physical or analog models, mathematical models provide varying degrees of tangible representation of the system that is being simulated. The types of mathematical models are stochastic or deterministic while solution techniques may be analytical or numerical.

Application of a stochastic model attempts to recognize that parameters do not have a single value over the domain of the aquifer. Instead, a parameter is likely to have a certain probability distribution, even for a relatively homogeneous material. Stochastic models attempt to account for this variance in the basic parameters by determining or assuming a probability distribution function (pdf) for some model input parameters. For example, hydraulic conductivity generally has a log-normal distribution, while other parameters may have normal distributions. The stochastic model (for example, the Monte Carlo method) randomly samples from the input parameter distribution and calculates a result. After a large number of iterations, possibly hundreds, enough data points are accumulated to identify a probability distribution for the output parameter. Initial data requirements can be large (to adequately determine the input variable distributions) and computer run time can be high (to provide the number of runs required to determine the output pdf). Stochastic models are rarely used except for very simple flow model situations.

Analytical models are equations that are the closed form solutions to the governing equations for flow and transport with appropriate boundary and initial conditions. In order to obtain the closed form solution, it is often necessary to assume a simplified aquifer condition, simple boundary conditions, and single values (no spatial distribution) for the input parameters. Depending on the situation, an analytical model may or may not be a good choice for accurately determining output parameter values for a specific site. However, it may be possible to select conservative values for the parameters and construct a worst-case scenario. If this approach provides satisfactory results, more detailed (i.e., numerical) modeling may not be necessary. Analytical models are generally used for simple systems and for screening types of analyses.

Numerical models employ a variety of numerical approximation methods to represent the partial differential equations that govern flow and transport. These include finite difference methods that use algebraic approximations, finite element methods that use minimization of residuals of weighting functions integrated over the model domain (Galerkin method), or approximations of equation forms over typical conditions of groundwater flow, such as the method of characteristics. Examples of numerical models using these various approaches are MODFLOW, AQUIFEM, and MOC, respectively. These approximations are applied over each model element or node, giving rise to a set of simultaneous equations that may then be either directly solved by matrix inversion methods, or, more typically, by iterative procedures that are more efficient than the matrix methods when large arrays are involved. Data requirements and levels of effort are generally much greater for numerical models than for analytical models.

The basic difference between analytical and numerical models is the degree of simplification that is assumed for the boundary conditions and physical system being modeled. The choice between selecting an analytical model or a numerical model may be a function of the goals of the modeling, available time and budget, and the quantity and quality of data for the site. Some modelers, however, will construct preliminary models with very little data and use the model as an aid to developing the field program. Often an analytical model, calculated for limiting (maximum or minimum expected) values of parameters, may provide a satisfactory basis for a decision (e.g., quantifying the volumetric rate of flow of groundwater into a recovery trench), and thus save the considerable expense and time required for a numerical model. In any case, a good conceptualization of the aquifer system is required in order to evaluate the applicability of any given model, and to appropriately include consideration of the underlying assumptions of that model.

7.3-2 Analytical Models

Analytical models frequently assume a substantial simplification of the groundwater system, but they provide exact solutions to the mathematical expression. In analytical models, the flow is most often described as occurring in confined aquifers that are assumed to be:

- homogeneous and isotropic;
- infinite in areal extent;
- uniform thickness throughout;
- groundwater temperature, density, and viscosity are assumed to be constant;
- production and injection wells have infinitesimal diameters and no storage capacity or finite diameters with specified storage capacity;
- except for flowing wells, areal discharge and recharge to the aquifer are constant (and might not be included); and
- hydrogeologic boundaries usually are not addressed in the general solution. However, boundary problems may be handled by using image well theory (Walton, 1985).

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Darcy's law, one form of which is given by the expression:

$$q = KJ$$

where:
- q = specific discharge;
- K = hydraulic conductivity; and
- J = hydraulic gradient

is an equation of motion that reflects the most simple analytical model. Using it requires satisfying all of the conditions previously stated. If the hydraulic conductivity and hydraulic gradient are known, then the specific discharge can be quantified. Furthermore, given any two of the three parameters, the third variable can be calculated at any other location in an aquifer that has homogeneous, isotropic properties.

Other examples of analytical models include the Dupuit-Forcheimer discharge formula for flow in unconfined aquifers and Jacob's approximation of the Theis equation for predicting the transient drawdown response due to the influence of a pumping well. Some texts containing these and other analytical models include: "Hydraulics of Groundwater" (Bear, 1979), "Quantitative Hydrogeology" (deMarsily, 1986).

7.3-3 Numerical Models

Numerical models represent the equation of motion and statement of mass conservation of groundwater in an aquifer system. They rely on the same principles and equations as analytical models, but they generally require fewer simplifying assumptions. The theoretical basis for the governing groundwater flow equations is well documented and is based on a combination of Darcy's Law and the groundwater mass balance equation (Wang and Anderson, 1982; Mercer and Faust, 1981). Some of the principle input parameters necessary to construct a groundwater flow model at a specific site must be identified. These parameters include:

- the shape of the potentiometric surface for confined aquifers or the piezometric surface (i.e., the water table) for unconfined aquifers;

- the distribution of hydraulic conductivity, and depth to bedrock or transmissivity in the aquifer;

- the geometry of the aquifer; and
- the location and nature of recharge or barrier boundaries.

The potentiometric head (needed for model calibration) can be measured at selected locations in the field; transmissivity or hydraulic conductivity and depth to bedrock can be estimated with reasonable reliability using pumping or, if necessary, slug test data, boring log information, or a host of other field or lab tests (see Section 7.4-4.2 for greater elaboration); and the aquifer/aquitard geometry can be determined from boring log and pumping test information, surface geophysics and survey data. Geophysical techniques such as seismic refraction, electrical resistivity and ground penetrating radar are cost effective ways of characterizing aquifer geometry, stratigraphy and, to some degree, the depth to the water table.

The acquisition of this physical data, in conjunction with water quality results, is invariably limited in extent, principally because of economic considerations. It is, however, the primary and fundamental source of information upon which the model is constructed. Consequently, the inherent weakness associated with many modeling efforts is lack of sufficient data of usable quality. It behooves the project manager and modeler to continually be aware of this when conceptualizing and constructing models. It is also why the calibration procedure and sensitivity analysis are such an important part of the modeling process.

The discharge/recharge relationship of surface bodies of water (i.e., lakes, ponds and streams) within and adjacent to the aquifer needs to be identified in order to properly construct and calibrate the model. This data can be obtained by taking contemporaneous stream flow measurements at different locations in a stream or river during extended periods of little or no rainfall (three or four days) or by utilizing streamflow measurements at USGS gauging stations. The water that is in the stream channel during these times is referred to as base flow and represents almost entirely the groundwater portion of stream flow. Using a technique referred to as stream tube or flow net analysis, this information coupled with piezometric head data in the aquifer can be used to estimate the hydraulic conductivity in other parts of the aquifer. At the very least, this information will be needed to calibrate the model when the nodal water mass balance (i.e., the amount of water coming in and out of each node) is performed. Seepage meters may also be used to quantify flux between the aquifer and a surface water body. When used with piezometers below the streambed, hydraulic conductivity of the streambed can be estimated (Lee, 1978).

Gathering physical and chemical data for an aquifer is generally very costly and time consuming given:

- the geologic variability that exists in glaciated terrains such as New England; and
- the types and required detection limits of the contaminants that are being regulated.

That is why it is very important that the project manager, field geologist and modeler all have a good conceptual understanding of the hydrogeology of the aquifer. If the team lacks or is weak in any of these areas:

- a firm theoretical understanding of flow through a porous or fractured bedrock medium;
- the nature and characteristics of the contaminants in question;
- the influence that any production wells may have on regional flow;
- how the aquifer is bounded; and
- appropriate protocols for installing and sampling monitoring wells and conducting other field activities,

then the following will occur:

- a poorly defined conceptual model;
- the design and execution of an inadequate field sampling program;
- insufficient and/or inaccurate data with which to construct and calibrate a groundwater flow and, if appropriate, a solute transport model; and
- a poorly designed remedial strategy.

In most numerical models, the governing partial differential equations are approximated by algebraic difference expressions relating unknown variables (e.g., head, flux) at discrete points (nodes) at different times (Javandel et al., 1984). Consequently, more complex conditions such as heterogeneity and anisotropy can be more accurately simulated in numerical models than in analytical models. Typically, numerical models utilize more data than analytical models because varying aquifer properties may be described at numerous, discrete points within an aquifer. Complex or irregularly shaped boundaries such as leaky streams or impervious (i.e., no-flow) boundaries or a meandering river are generally easier to model using a numerical approach, while analytical models are severely constrained in this regard.

7.3-3.1 Finite-difference Technique

There are two common types of numerical techniques that are applied to groundwater problems: finite-difference and finite-element methods. Finite difference techniques solve the groundwater-flow equation by approximating the derivatives of partial differential equations at regularly or variably spaced points in the system. The finite-difference technique employs a grid of squares or rectangles as depicted in Figures 7-1(b) and (c). Figure 7-1(b) is a block centered representation of the aquifer shown in Figure 7-1(a), while Figure 7-1(c) is a mesh or node centered grid of the same aquifer. There is no significant difference between the two. If there are lateral variations in hydraulic properties within the aquifer, such as transmissivity or storativity that are linear in nature, use of a block centered grid makes it slightly easier to delineate and assign values to those regions.

Notice that in either case, (b) or (c), because of the perpendicular nature of the intersecting grid lines, some of the grid is either outside or inside the physical aquifer boundary. Since aquifer geometry and boundaries are rarely linear features, this condition will invariably arise. The only time that it may present a problem is if accurate piezometric data are desired adjacent to those features. If that is the case, then a finer grid size will result in a more accurate determination of piezometer head. However, a finer mesh will increase the number of nodes necessary to describe the feature, which in turn will result in greater computation time. This generally translates into an increased level of effort and expense in model construction and validation and computing costs.

7.3-3.2 Finite Element Technique

If the geometry or internal physical features are curvilinear, then it might be easier to model the aquifer using a finite element approach with triangular elements of varying size as depicted in Figure 7-1(d). Irregular aquifer or lateral internal variations in geologic properties (e.g., lateral changes in aquifer properties or irregularly shaped water bodies) can be more readily accommodated with a finite element mesh although the time necessary to construct the grid and input the data into the computer can be considerable.

The finite-element method approximates differential equations by an integral method. The model area is divided into sub-regions, or elements, and the finite-element model grid may consist of triangles or quadrilaterals. Numerical models utilize a variety of solution techniques to solve the resulting equations. Additional information on finite-difference and finite-element techniques and solution techniques is contained in numerous introductory modeling texts (e.g., Wang and Anderson, 1982; Walton, 1985).

7.3-4 Solute-Transport Models

Solute-transport models simulate the distribution of contamination as concentrations (i.e., mass per unit volume of a compound) in an aquifer by simultaneously solving both the flow equation and the transport equation. Physical, chemical, and biological processes all affect the rate and migration of contaminants in an aquifer.

Solute transport processes include physical phenomena, and chemical and biological reactions. Individual processes are, in some cases, fairly well understood under laboratory conditions and can be somewhat replicated under field conditions in saturated porous media. Solute transport in fractured bedrock is much more difficult to identify and characterize because of the heterogeneous anisotropic nature of the aquifer. In addition, when multiple contaminants are present that respond differently to different processes in either media (unconsolidated or bedrock), the resulting synergistic reactions become difficult to model. Thus, real problems arise in very heterogenous or fracture-dominated systems or when nonaqueous phase contaminants or solutes that react with solid, liquid or biological components of the subsurface are present. These cases, and they are common (i.e., gasoline spills, metals, organic solvents, etc.), can be very difficult to model. Consequently, this greatly limits the reliability of using mathematical models of solute transport to predict future site conditions for such situations.

The basis for the selection of values of various input parameters for solute transport models, such as dispersion coefficients, is still being debated. Another required input parameter, which is generally not well defined, is the strength of the contaminant source. Also, input parameters for the transport equation, such as dispersion coefficients and biotransformation rates, are difficult to quantify in the field with available technology, particularly in groundwater regimes where flow is very slow.

Assessment of solute transport requires a multi-disciplinary approach that integrates the geologic, hydrologic, chemical, and biologic processes and features that are important at a site (Keely, 1987). A complex array of chemical wastes and a poorly documented contaminant release history are associated with most contaminated sites, thus making solute-transport modeling a difficult proposition. Some of the known factors that influence the fate and transport of contaminants are listed on Table 7-1. At the present time, there are many gaps in our understanding of solute-transport phenomena and the appropriate methods for characterizing them.

Of the physical processes affecting solute transport, advection, a flow dominated process, is the most well understood parameter. Recent studies (Sudicky, 1986) indicate that advection may be the dominant control in the physical processes of solute transport and that the delineation of the complex and difficult-to-measure parameters such as dispersion or diffusion may be unnecessary. These studies suggest that a detailed description of the distribution of hydraulic conductivity in an aquifer may be the most important factor in simulating solute-transport, although obtaining this data could be economically prohibitive. Hence, in order to predict contaminant transport adequately, it is imperative to have a well-calibrated groundwater flow model. Other researchers, however, suggest that calculations of travel time based solely on advection and longitudinal mechanical dispersion may greatly underestimate breakthrough of the solute (Keely, 1987). Finally, under certain circumstances, for example, when flow velocities are extremely low (e.g., when leachate passes through clay liners), molecular diffusion becomes the controlling component for solute transport, unless there are conduits for vertical flow through the clay liners such as cracks, roots, etc..

The measurement and mathematical description of chemical processes in the subsurface are less certain than the physical processes affecting solute transport. Although parameters such as ion exchange and oxidation-reduction reactions are well understood in the laboratory, their application to field conditions is difficult. In addition, the complex interaction of various organic and inorganic compounds that are often present at contaminated sites is difficult. The solute-transport models currently available do not take these chemical and geochemical interactions into account.

Biological processes are another set of frequently overlooked parameters that affect the fate and transport of contaminants. These processes include the biotransformation of one compound into another as the result of subsurface biological activities. Although the presence of these processes is recognized, the factors influencing the rates, abundance, and impact of these processes are not well defined. The effect of biological processes on solute fate and transport is currently an area of intensive research and, as these processes are better quantified in the field, they may be able to be more accurately modeled.

Due to the complex nature of the interactions of these processes, it is often necessary to make assumptions and simplifications to obtain mathematically manageable solutions (Keely, 1987). In many cases, the impact of certain parameters must be ignored completely in order to describe the problem mathematically. The magnitude of errors arising from these assumptions and simplifications must be carefully evaluated.

For example, transport models, which only consider advection and dispersion, are not likely to be representative of a case where contaminants may be removed by a process such as adsorption. Consequently, the accuracy and applicability of solute-transport model simulations must be reviewed in light of the assumptions made during the modeling phase. Until there is a better understanding of all the subsurface processes affecting solute transport, the results simulated by solute-transport models should be applied with caution when making remedial and/or regulatory decisions with regards to a site. Use of conservative values for transport parameters can, however, establish reasonable limits to expected concentrations. Under worst-case conditions, it may be possible to establish acceptable risk criteria for a site.

7.3-5 Application of Numerical Models to Groundwater Flow Problems

Numerical models can be applied to a variety of groundwater problems to increase the user's understanding of the natural flow system and how the flow system might respond to various stresses, both natural and man-made. Models can be used either for interpretive or predictive purposes to simulate how a particular aquifer may respond to recharge, pumping wells, or some other form of hydraulic remedial action. Models can also be useful tools for designing a subsurface monitoring program for site investigations or long-term monitoring. Typical applications of numerical models include:

- Testing and improving the conceptual model of a ground water flow system initially formulated on the basis of field observations;
- Evaluation of the impact of various activities on groundwater quantity (aquifer stress and yield);
- Evaluation of the effectiveness of alternative remedial pumping schemes;
- Evaluation for risk assessment purposes of the potential exposure of receptors to various contaminants over time;
- Definition of well head protection zones;
- Evaluation of saltwater intrusion; and
- Design of monitoring well networks.

7.3-6 Modeling Limitations

An important step in any modeling program is to determine if the construction of a mathematical model is appropriate and necessary. Figure 7-2 is a flow chart for determining whether or not modeling is required. Often times, gathering additional data will improve the conceptual understanding of the site; however, a cost benefit analysis that considers the goals of the investigation should be performed prior to collecting more data.

In some cases, models are used to predict current groundwater contaminant concentrations at potential exposure points, utilizing only data near the contaminant source. Project managers should constantly evaluate whether simply gathering real, current data at the potential exposure points is useful and beneficial.

Because of the sometimes extreme heterogeneity of the geologic environment or the potential for different interpretations of the same hydrogeological data set, a good modeler should always take a conservative approach in evaluating the validity of the model in its ability to estimate some prior or future condition. Embarrassing stories abound in modeling circles concerning the discovery of previously unidentified geologic features identified with subsequent drilling programs, which, by their presence, necessitated major revisions to the conceptual and numerical model. Models aid in understanding how a system works, but room for refinement of that understanding always exists.

7.4 PROCEDURES FOR CONSTRUCTING A NUMERICAL FLOW MODEL

7.4-1 Modeling Team

At a minimum, the modeling team should consist of the modeler and the site geologist/hydrogeologist or engineer skilled in groundwater hydrology. The site project manager need not be a geologist/hydrogeologist. The modeler should conduct one or more site visits and frequently discuss the model with the site geologist/hydrogeologist with regards to where he/she feels the weaknesses of the model exist and what kind of information he/she needs to strengthen the model. Under no circumstance should the modeler construct the model without consulting with the site geologist/hydrogeologist, unless he/she is also the site geologist/hydrogeologist or has conducted the field work.

The model selected for use on a project should vary according to site conditions and modeling requirements. The level of experience of the modeler should also vary with the more experienced modelers constructing the more complex models. Depending upon the size and complexity of the model and staff availability, a less experienced modeler should serve as an aid to the principal modeler assisting in grid construction, data entry and performing the computer runs. In this way he/she gains more experience in learning how to construct and calibrate more complex models.

If a solute transport model is also required, then depending upon the contamination that is being modeled, a chemist in the particular branch of chemistry in question should be part of the modeling team. That individual should review the geologic and chemical data and participate in the development of the conceptual model. The types of contaminants that can be modeled include:

- inorganics (including metals);
- volatile organic compounds;
- acid/base neutral compounds;
- dense or light non-aqueous phase liquids (DNAPL or LNAPL, respectively); and
- radioactive compounds.

All of these classes of compounds have different physical, chemical and biological properties and will behave and react differently in the aquifer and in some cases with each other as well. For some chemicals (e.g., for a DNAPL plume) and/or some aquifer conditions (i.e., fractured bedrock) acquiring sufficient data could be extremely difficult.

Another important requirement for a modeling program is time. Where analytical models may take an hour or a day to set up and evaluate, numerical models, depending upon their size and complexity, may require weeks or months to properly design and calibrate.

7.4-2 Conceptual Model

The conceptual model is the modeler's and project geologist/hydrogeologist's concept of how the physical hydrogeological system works. It includes a discussion of all of the controlling factors in the system, such as aquifer extent and thickness, sources, sinks, and hydrogeologic boundaries. Alternatively, it may be a working hypothesis that the modeler wishes to test. In addition, the conceptual model becomes the basis for developing future data gathering efforts. Any model is only as good as the conceptual model and its ability to capture the essential elements of the hydrogeologic system.

A conceptual model should be developed whenever a site is being evaluated irrespective of whether or not a model is to be constructed. It is a "picture" in the project manager's mind of what the site subsurface and groundwater flow conditions are. It is, or should be, continually refined as new data are acquired. The development of a conceptual model should begin as the first pieces of information are received. Activities as rudimentary as review of a topographic map, hydrologic atlas or conducting a site visit should begin to stimulate ideas or "concepts" about the site hydrogeology. As more data is gathered and reviewed (e.g., aerial photographs, boring logs, prior reports, etc.), the site geologist/hydrogeologist should continually be refining his/her mental image of the aquifer. The evolution of the conceptual model is the primary responsibility of the site geologist/hydrogeologist not the modeler. The site geologist/hydrogeologist synthesizes all of the data and presents the conceptual model to the modeler for review and discussion. The modeler then reviews the conceptual model and depending upon the goals the modeling effort may have some specific data needs or requirements in order to fulfill those goals. The subsequent field work initiated for the project should, costs permitting, attempt to fulfill those goals.

Very often contamination exists at the site (i.e., a leaking UST, a lagoon, a waste pile). A conceptual model of the waste source and its migration pathway(s) to the subsurface also needs to be developed simultaneously and integrated with the conceptual flow model. This should be done irrespective of whether or not a solute transport model is to be constructed as it will aid in locating monitoring wells or sampling locations.

Whatever the type of model to be constructed or used (i.e., analytical or numerical), a conceptual model of the aquifer needs to be created. As dictated by the site complexity and level of effort requested by the private party or DEP and the goal of the modeling effort, the conceptual models should include, but not be limited to:

- sketches;
- cross-sections;
- block diagrams;
- flow nets in map view and in cross-section;
- aquifer geometry;
- distribution of geologic materials both laterally and vertically;
- nature of the underlying bedrock;
- description of lateral aquifer boundaries (i.e., valley walls, streams, etc.);
- a discussion of major withdrawals or recharge to the aquifer;
- leakage from overlying bodies of water;
- wetlands or underlying aquifers;
- the nature of any confining units that might be present;
- the gaining or losing nature of any streams or rivers within or adjacent to the aquifer;
- horizontal and vertical hydraulic gradients;
- hydraulic conductivity and storativity of the different geologic materials in the aquifer; and
- the distribution of natural recharge across the aquifer.

In general, the more complex the site, the greater the level of effort is required to evaluate its hydrogeology and the more detailed is the conceptual model with fewer simplifying assumptions. Conversely, a simple site requires a lower level of effort and results in a less detailed conceptual model. Modelers should not extend a limited data set in order to achieve results for a complex set of goals.

7.4-3 Selection of an Appropriate Model

The selection of the type of model should be based on the objectives of the program, the complexity of the system, and the available data. According to de Marsily (1986), situations where the construction of a numerical model may be more suitable than an analytical model include:

- needing to identify migration pathways and predict end point receptor concentrations;
- having boundary conditions (either flow or no-flow) with complex shapes and/or situations where assuming infinite areal extent, constant aquifer thickness, and homogeneous, isotropic conditions or the use of image wells cannot adequately describe the system;
- having a non-linear problem where no analytical solution is available.
- varying aquifer geometry that is too intricate to be adequately represented with an analytical model, i.e. single values of hydrogeological parameters selected for the analytical model are inadequate for describing the real system; and/or
- having an analytical solution available, but which is very time-consuming or complex to calculate.

Selection of the most appropriate numerical model should be based on site conditions, the purpose of the modeling exercise, and the availability of data to adequately construct and calibrate the model. For example, a two-dimensional (2-D) groundwater flow model is appropriate if groundwater flow can reasonably be assumed to be horizontal. In constructing a 2-D model, if vertical heterogeneities exist in the aquifer, vertically averaged values of hydraulic conductivity can be calculated and used as input data. A cross-sectional or profile model can be constructed when consideration of vertical flow is important. The profile, however, needs to be constructed along a flow line.

A three-dimensional (3-D) model is appropriate if flow or solute transport in the third dimension is important to the understanding of the site hydrogeology (e.g., during pumping simulations in the vicinity of the pumping well, or where leaky aquitards are present, where the vertical distribution of head is of major interest, or where significant vertical heterogeneities exist). Three-dimensional models are also very useful in areas where groundwater flow is controlled by topography which may give rise to the presence of local, intermediate and regional flow systems resulting in complex vertical flow conditions.

For any numerical modeling effort, however, there must be sufficient data collected to support its construction, calibration and validation. Obviously, when constructing a three-dimensional model, the data requirements are significantly greater than for a two-dimensional model. For example, a number of well nests or well clusters are necessary in order to calibrate a 3-D model which greatly increases the cost of the field effort and the length of time necessary to complete it.

When aquifers that have vertical variations in composition and/or have vertical differences in hydraulic head or situations where it is important to know the vertical distribution of head are going to be modeled three dimensionally, multi-level or multi-port wells need to be installed in areas where vertical changes in head are anticipated. Not only is this an expensive and time consuming process, but constructing, calibrating and verifying a three dimensional model becomes very time consuming and expensive as well. For these situations, there has to be an extensive amount of field work of sufficient adequacy to achieve the desired objective.

What constitutes a "sufficient" data set is a matter of interest that deserves some discussion. Geostatistical software packages are available that are used for parameter estimation. "Kriging" is just one of a handful of techniques that is used to take a known data set and interpolate between those values as well as assign a confidence interval for the estimates that have been calculated. Another way of kriging data is to evaluate the data set of a number of values from one well (e.g., water quality) to arrive at a value that is representative of the entire set. Another way of stating the above is that kriging is the process of finding the best linear unbiased estimate at a point (or the average over an area) by linear interpolation from the variable data (DeMarsily, 1986).

The confidence interval of the estimate will vary depending partly upon the number of samples. The data sets for hydrogeologic investigations for the most part are rather limited. Consequently, the estimated confidence interval needs to be looked at carefully. For example, interpolation of a water table data set for an unconfined aquifer (i.e., a water table map) and a map showing the areal distribution of hydraulic conductivity might have similar confidence intervals. However, given the nature of the two parameters, hydraulic head (which spatially varies fairly uniformly and is rather damped) and hydraulic conductivity (which may be randomly distributed), the contoured map of piezometric data is less likely to significantly change with the acquisition of new data than the hydraulic conductivity map.

7.4-4 Data Compilation

A significant amount of data is needed to construct an accurate numerical model. Typically, a model begins with the construction of a series of maps and stratigraphic cross-sections that describe the aquifer conditions. This information is generally compiled by members of the field investigation team or modeling team and has as its basis the conceptual model that has been developed for the site. Because the conceptual model evolves continually, it is not unusual for the conceptual model to be refined as the data is compiled and depicted in the various types of maps and figures that hydrogeologically describe the site. Input data for a numerical model usually consist of, at a minimum, the items described below.

7.4-4.1 Geometry of the Aquifer System

The geometry of the aquifer system consists of a physical description of the aquifer including the geologic units, their vertical thicknesses and lateral extent. This information is obtained from subsurface borings, surface and borehole geophysical data, surficial mapping, an understanding of the geomorphology and depositional environment, and the construction of geologic cross-sections.

A minimum number of contoured maps should be developed prior to model construction. For a water table aquifer, they are:

- a hydraulic conductivity map;
- an aquifer bottom elevation map (this may or may not be equivalent to a bedrock topographic map;
- a land surface topographic map;
- a map of the elevation of water table; and
- a porosity map, if solute transport is being modeled.

For a confined aquifer, maps depicting the lateral distribution of transmissivity (rather than hydraulic conductivity) in the aquifer and the potentiometric surface are required. In some cases (e.g., transient flow modeling), maps depicting the distribution of specific yield (water table aquifer) or storativity (confined aquifer) may be required. This latter information is generally difficult or expensive to obtain in the field and globally assumed values from published literature are often used in the model. However, depending upon the types of geologic materials present, it may be desirable to use different published values in different parts of the aquifer (e.g., till upland adjacent to stratified drift).

It is not unusual for modelers to use equations for confined aquifers to estimate responses in unconfined aquifers (i.e., holding transmissivity constant), particularly if the dewatering effects in the area of concern are minimal. (Note: dewatering lowers the water table and reduces the saturated thickness, which in turn results in a lower transmissivity.) The advantage to doing this is that data compilation and entry time are significantly reduced. This approach is more acceptable in regions that are distant from a pumping or recharge well or where seasonal changes in the water table are small. The model will accurately reflect head values in those areas. Where dewatering is significant (greater than approximately 10% of the saturated thickness), this approach is not recommended and should not be used without correcting the drawdown for the dewatering effect.

7.4-4.2 Transmissivity

The transmissivity of the aquifer can be obtained directly from pumping tests as well as from other methods. In order of preference, they are:

- pumping tests,
- field tests of hydraulic conductivity (i.e., slug tests),
- dividing estimated regional flow by measured hydraulic gradient,
- laboratory permeability tests on the soils,
- grain size analysis, or
- published data.

When hydraulic conductivity (K) is obtained directly (i.e., slug tests, grain size, etc.), the saturated thickness of the aquifer (b) must be estimated so that the transmissivity (T) can be calculated (T=Kb).

Pumping tests, particularly large capacity tests, are the preferred way to estimate transmissivity over large regions of the aquifer. Transmissivities derived from pumping tests are less satisfactory for solute transport models where variations in hydraulic conductivity are more important than average conductivities over a large region. Very often in dealing with contaminated sites, pumping tests, prior to the treatment system being operational, are run at much lower volumetric rates to minimize the extraction of contaminated groundwater and consequently impact a smaller region of the aquifer. Slug tests measure the hydraulic conductivity only in the immediate vicinity of the monitoring well and care must be taken in extrapolating those results very far from where the measurements were taken. Regional flow can sometimes be approximated based on estimates of areal recharge and the upgradient recharge area. Using Darcy's Law, this flow can be divided by the measured gradient and flow tube width to approximate transmissivity. Laboratory tests for hydraulic conductivity require physically taking samples of the aquifer into a soils lab for permeameter testing and/or for sieve analysis (see Section 3.8-1). In doing this, the soil structure (packing) is disturbed which will alter the hydraulic conductivity. In the absence of field data, published tables may provide reasonable estimates of hydraulic conductivity.

7.4-4.3 Storage Coefficients

The storage coefficients and/or specific yields are also necessary input parameters for transient simulations. Storage coefficients can be determined through aquifer tests, and specific yield can be estimated through aquifer or matrix and void space volumetric tests that are performed in the laboratory. If these data are not available, assumed values for these parameters are often used. An order-of-magnitude value is often assumed for the confined storage coefficient. Specific yield or unconfined storage coefficients can be estimated much more closely.

7.4-4.4 Identification of Surface Water Features

The locations of surface water bodies are also necessary for model construction. Locations usually can be obtained from topographic maps or from aerial photos, although more accurate information regarding these features is generally obtained in the field. The hydraulic connection and flux (i.e., leakage, induced infiltration, or groundwater discharge) between these surface water features and the groundwater system will need to be quantified.

7.4-4.5 Leakage

Leakage rates from semi-confining layers, or induced infiltration or leakage from lakes, ponds and streams can be determined by analyzing data from a well-designed aquifer test or estimated from the geologic description of the adjacent units, based on their estimated thickness, permeabilities, and vertical head differences. Seepage meters and streambed piezometers can also be used to quantify flux from an adjacent surface water body into or out of an aquifer (Lee et al., 1978).

7.4-4.6 Delineation of Discharge and Recharge Areas

Depending upon the goal of the modeling effort, the location and rate of recharge to the system through precipitation, infiltration, and or injection should be determined based on field measurements or estimated from available geologic and climatological data. Zones where groundwater is extracted from the aquifer system through pumping or natural discharge to surface waters should be identified and quantified to the extent possible. Measurement of pumping rates and temporal variations in pumping rates from wells and the use of stream-gauging and seepage meters in streams and swamps can provide data to help quantify these factors.

7.4-4.7 Piezometric Heads

Piezometric head data are required for the construction, calibration, and validation of a model. These data are obtained from water-level measurements made at various locations and depths in the aquifer. This information can be compiled in the form of water-table and piezometric maps or hydrographs for specific wells. The collection of head data over a period of several years may be required to determine long-term (steady-state) conditions in an aquifer. For 3D models, piezometric measurements should be made in all aquifer layers that are being modeled in order to achieve a good calibration.

It is not unusual for a site to be investigated over a period of years with the modeling effort coming in the later part of the project. Consequently, it behooves the project manager to have water levels measured at a minimum on a quarterly basis until the hydrogeology is understood. Once that occurs, semi-annual measurements (preferably in late spring and fall) can be taken. The U.S. Geological Survey (USGS) has a network of long term monitoring wells in the state that are measured on a monthly basis. This data should be used, when appropriate, to supplement site-specific data. Techniques for predicting probable high groundwater levels in Massachusetts and on Cape Cod are available from the USGS (Frimpter, 1980 WRI-OFR 80-1205 and Frimpter, 1980 WRI-OFR 80-1008, respectively).

7.4-5 Definition of Boundary and Initial Conditions

In order to solve the partial differential equations that define the flow regime, the nature and location of the hydrologic boundaries need to be determined. This information may be based initially on a conceptual model of the flow system, however, the existence of boundaries must be verified in the field. Models should maximize the use of any field measurements of stream and pond elevations, or discharge and recharge rates, as well as the physical location of aquifer boundaries. When transient conditions are simulated, initial conditions are also required. For example, in a simulation of flow through an unconfined aquifer, the initial piezometric head values are assumed at the node locations within the aquifer. These head values represent the initial conditions for the transient (non-steady state) simulations.

In some cases the natural limits of the aquifer may be extremely far from the area of interest in the model. In this case artificial boundary conditions may be used, such as constant-head (i.e., an equipotential line), constant flux, or no-flow boundaries (i.e., a groundwater flow line). In applying these artificial boundary conditions to the model, it is assumed that these boundaries will not be significantly affected by the simulation. If pumping or recharging wells are influencing these boundaries, then the model will need to be reconstructed so as to minimize this interference. The appropriateness of these boundary conditions should be checked to determine their influence on long-term predictions of the model (de Marsily, 1984). This can be accomplished by replacing a constant-head boundary with a specified-flux boundary and running the model again. If the differences in the two simulations are insignificant, then the artificial boundary conditions are not significantly affecting the simulation. Note, however, that the model still might not be valid due to failure of other criteria, which are discussed in Section 7.6-3, Sensitivity Analysis.

7.4-6 Construction of the Model Grid

Once the conceptual model has been formulated, the model grid can be constructed. This process is often referred to as discretization. The design of the grid will affect the accuracy of the piezometric approximations at specific locations in the model, as well as the amount of time necessary to run the model on a computer.

A general rule of thumb to follow is that if variable grid spacing is to be used, then the node or grid spacing should become smaller whenever there are abrupt changes in: 1) physical properties (e.g., a till-stratified drift contact); or 2) piezometric head (e.g., adjacent to a production or recharge well). Referring to Figure 7-1(a), (c) and (d), the node spacing in the vicinity of the production wells is much closer than along the model boundaries. The closer grid spacing will provide better resolution of piezometric head in those areas. The trade off for having a finer grid spacing is that in doing so, the number of nodes generally increases which results in greater computational time. This may seem insignificant for a two dimensional model, but can become significant for three-dimensional models. This can be compensated to some degree by creating larger grid spacing away from the areas of interest (e.g., near the model boundaries (see Figure 7-1(d)). With regards to node spacing, some finite difference codes recommend that an adjacent node be no more than 1.5 times the distance between the last two nodes.

The following general guidelines (modified after Mercer and Faust, 1981) should be followed when designing a model grid:

1. Place nodes at pumping centers and monitoring/observation wells. In the case of a tubular well field (i.e., a series of small diameter wells manifolded together), a number of wells can be grouped together at one node.

2. Accurately locate model boundaries so that they correspond with real hydrogeologic boundaries. As depicted in Figure 7-1, finite element techniques can approximate curvilinear boundaries and other features better than finite difference techniques. The loss of this kind of detail is not significant if knowing exact piezometric heads in those areas is not important.

3. Place nodes close together in areas where there are large variations in geologic conditions or anticipated, significant changes in hydraulic head (for example, near pumping or recharging wells). What defines "close" is really a function of the size of area to be modeled, the number of nodes that are available, and the particular solution technique utilized in the code. The larger the area, the greater the node spacing. The limiting factors are either the software (some codes have a 2,500 node limit) or the hardware (available memory capability).

4. Align the axes of the grid along major directions of anisotropy or heterogeneity.

7.4-7 Assignment of Parameters to Nodes

Once the basic data have been compiled and the model grid has been designed, model parameters can be assigned to each node. At this point, the physical aspects of the aquifer are defined for each node in the model by overlaying the model grid over maps of saturated thicknesses, transmissivity, initial conditions, and other features. The properties are assigned to each node of the model and comprise the input files for the model.

Keying the data into the computer on a node-by-node basis is a time consuming process and incorrect data can often be entered for a node. It is important to check the input data very carefully prior to running the model. It is pointless to attempt to calibrate the model if the input data is in error. Some errors become apparent only when first attempting to run the model, particularly when using a new or unfamiliar model. The user should plan on some initial debugging runs to aid in correcting input data files.

7.5 PROCEDURES FOR RUNNING A NUMERICAL FLOW MODEL

7.5-1 Model Calibration

Calibration of the model consists of running the model and comparing model-simulated heads to a set of field-measured heads and, where applicable, model-simulated rates of groundwater discharge to a set of field-measured rates of groundwater discharge. This is accomplished through a trial-and-error process of varying aquifer parameters (e.g., transmissivity, storativity, recharge, etc.) in different regions of the model (having, of course, some justification for making the changes) until the match between model-simulated and field-measured conditions is considered acceptable. Calibration can be performed to steady state or average head conditions or to transient conditions. Other calibration criteria include a water mass balance, groundwater discharge to streams (i.e., gain or loss), and, if the model is a three dimensional one, vertical and horizontal head distributions in all layers.

There is no textbook definition of what constitutes an "acceptable" match between simulated and measured data. Simulated data will rarely exactly match measured data, however, the difference between the two should be minimized. Two methods of comparing simulated to measured data are to calculate the absolute average difference (AAD) or to calculate a standard deviation and root mean square error (RMSE) for all the data. If the standard deviation and the RMSE is small or if the AAD is small, then the calibration is considered acceptable with the following exception.

There will invariably be outliers, that is, locations or nodes where the difference between simulated and field data is substantial. If those nodes are in central areas of the model where predicting heads for future scenarios is desired, then the model calibration should not be considered "acceptable". If, however, those nodes are distant from where forecasting information is sought (e.g., a till upland region adjacent to the aquifer), then this difference often times will have little impact on the modeling results.

A word of caution against too finely tuning a model may be justified here. A more generalized model that calibrates reasonably well may be more valid than one in which the RMSE is very small, but its parameters have been very finely tuned in areas where there is no field data to verify that these changes are warranted.

Also, care must be taken when constructing the model using interior constant head nodes. A river or lake that is large enough and in good hydraulic communication with the aquifer may be represented with a series of constant head nodes. However, if a water body is shallow and susceptible to large fluctuations in water level elevation, constant head nodes may not be the best representation.

A detailed log of the adjustments that have been made to the input data during the calibration process should be maintained. This will provide a record of the modifications made to the original entries and should help to avoid repeating calibration runs. During the calibration phase, the modifications should be checked against the original conceptual model to ensure that the model is still representative of the physical system. It is easy to stray from the original concept of the system during the calibration process.

The reliability of the model is related to the accuracy with which the model simulates field conditions. It is important to keep in mind, however, that just because the model reproduces one set of field conditions does not mean that it is valid. Modification of different sets of parameters can produce similar solutions. Consequently, the calibration of the model must be performed systematically and with a good understanding of the site conditions. For a particular site, given the proper assumptions, additional field data will often improve the accuracy of the model. Many times it is necessary to perform additional field work to fill in data gaps before an accurate model is obtained. The decision to obtain further data must include a careful weighing of benefit to the model (reflecting model goals) and cost and time involved in obtaining the additional data.

7.5-2 Model Validation

Upon conclusion of the calibration process, the model should be run with a different set of initial conditions produced by a different set of stresses than the initial calibration (e.g. high vs. low water table or pumping vs. non-pumping conditions). Because of the non-uniqueness of the solution, the model should be validated with as many sets of initial conditions as may exist prior to using the model for any forecasting. Preferably, data should be collected at periods of seasonally high and low water tables in order to reflect seasonal fluctuations in recharge and surface and groundwater conditions. Confidence in the reliability of the modeling predictions can only increase as a result of this exercise although no model can ever be fully validated. See Van der Heijde (1986) for a more detailed description of validation procedures.

7.5-3 Sensitivity Analysis

Once a model has been calibrated and validated, a sensitivity analysis should be performed on the model. This is accomplished by varying the values of input parameters where there is little field control and evaluating the resultant distribution in heads. If the model is very sensitive to reasonable changes in a parameter value (e.g., transmissivity, recharge, leakage), then caution should be exercised in interpreting results from the model, particularly under applied stresses differing from calibration conditions. Depending upon the importance of the forecasting capability of the model, (i.e., does the possible range of outcomes preclude adequate selection of alternatives or prediction of impacts), more field work may be required to decrease the uncertainty of the model in that area.

If the area where the uncertainty exists is in a remote part of the modeled area, determining more precise physical conditions may not be necessary. Leakage from or to a stream, however, may greatly alter head levels in an adjacent production well and hydrogeologic data will need to be more accurately quantified in that area. A sound conceptual model will aid in identifying sensitive areas early on in the program.

7.5-4 Forecasting

Upon completion of the calibration and verification procedures and at the conclusion of performing the sensitivity analysis, the model can be used to simulate past, current, and/or future conditions. One advantage of a numerical model is that, once calibrated, it can be used to simulate a variety of situations. A flow model can be used to predict the response of an aquifer to conditions of average or excessive recharge or to a drought. If a model is being used for long-term planning and prediction, it should be periodically recalibrated as new data becomes available. Caution should be exercised in attempting to use the model under conditions much different than those under which it was formulated and calibrated/validated.

7.6 REPORTING MODEL RESULTS

7.6-1 Presentation of Results

An important but often overlooked aspect in the use of groundwater models is the proper presentation of modeling results. In order to present modeling results in a systematic, clear and effective fashion, the following format is suggested. This format is an adaptation of the DEP Division of Water Supply's published Policy 87-12, "Quality Assurance for Groundwater Modeling".

7.6-2 Purpose

State the purpose, goals, and objectives of the modeling effort.

7.6-3 Conceptual Model

Develop and present a conceptual model of the aquifer system and, if applicable, the contamination problem of concern (i.e, existing distribution of contaminants and source characteristics). This should include cross-sections and maps of the geology and hydrology of the aquifer at an appropriate scale, including maps of the areal extent of the aquifer and if applicable, distribution of contamination, saturated thickness, water table and boundary conditions maps. Present pertinent available data with a discussion of their deficiencies.

7.6-4 Data Collection

Explain how, when, and by whom the data were collected, analyzed, and interpreted. Exploration methods and data-analysis techniques should be presented. The level of confidence in resulting parameter identification should be described. Describe how model results may be limited or restricted by the lack of knowledge about key aspects of the hydrogeologic system.

7.6-5 Model Description

Document the groundwater flow and contaminant transport model (software) that is being utilized. Include such information as the model name, its author(s) and the purpose for which the software was developed. The use of well documented and tested software is recommended over the use of custom or altered software. If an altered code is utilized, it should be thoroughly tested against a variety of known analytical solutions. The documentation must include the governing equation(s) being solved.

Explain why the model being utilized was chosen. All simplifying assumptions inherent to the application of the model should be stated and justified, as well as the impact these assumptions may have on model results. A comparison between these assumptions and actual conditions should be made. Describe where model assumptions and actual field conditions do not coincide and how this may affect model results.

7.6-6 Assignment of Model Parameters

All initial conditions, boundary conditions, hydraulic and transport parameter values should be defined and the reasons for selecting these conditions justified. The values assigned throughout the modeled area should be presented. The area covered by the model should be presented as an overlay on a topographic base map of appropriate scale, highlighting boundary conditions and hydraulic parameter values.

7.6-7 Model Calibration

Model calibration goals and procedures should be presented and discussed. The results of the final calibration run should be presented and analyzed and departure from the calibration targets analyzed. The effects of these departures on the model results should also be discussed.

7.6-8 Model Validation

If model validation has been performed, its goals and procedures should be presented and discussed. The results of the validation run should be presented and analyzed. Important points include departure from the validation targets and the significance of these departures. Present and discuss the overall model water and chemical balance, highlighting salient features of the model scenario (e.g., pumpage, recharge, leakage, or boundary conditions). Ideally, the validation should consist of a single run (per validation data set). If the validation run is not successful, but information is obtained of a suitable nature, it may lead to re-evaluation of the conceptual model and possible changes and further calibration.

7.6-9 Sensitivity Analysis

Model sensitivity analysis should be presented and interpreted. Determine what parameters of the model have the greatest influence on the model results. The analysis should focus on those parameters that utilize the least certain assumptions. Also indicate, on the basis of the sensitivity analysis, what the emphasis of future data collection efforts should be best to improve the model.

7.6-10 Data Preprocessing and Postprocessing

All preprocessing of model input data must be thoroughly described. Special precautions to avoid data input error must be applied and described. All postprocessing of model output data must be thoroughly described and any computer codes utilized must be documented. Note vertical exaggeration in any computer-generated cross-sections.

7.6-11 Model Prediction

The model output from all predictive scenarios should be presented and interpreted. Present and discuss the overall model water balance for each specific forecasting scenario. Show results in terms of new head distributions, rates of groundwater discharge, distribution of concentrations, and so forth. Discuss how model sensitivity and uncertainty could affect the predicted results.

7.6.12 Model Results

The physical reality of the model should be discussed (i.e., how well does the model represent the physical and chemical processes of the environment being simulated?). Restate the fundamental assumptions in the presentation of the model predictions. Note if the model results support the initial assumptions described in Section 7-7.4.

The model results should be presented both in technical and non-technical (i.e., layman's) terms. Model results should also be qualified, for example: "Given conservative values, within the range of expected variation, the model results show..." or "Given less conservative values within the range of expected variation, the model results show...".

7.6-13 Model Records

The modeler should provide/keep the following records on file in digital form:

- The version of the source code utilized;
- Input parameters, boundary and initial conditions;
- The final calibration run (input and output files); and
- All predictive runs (input and output files).

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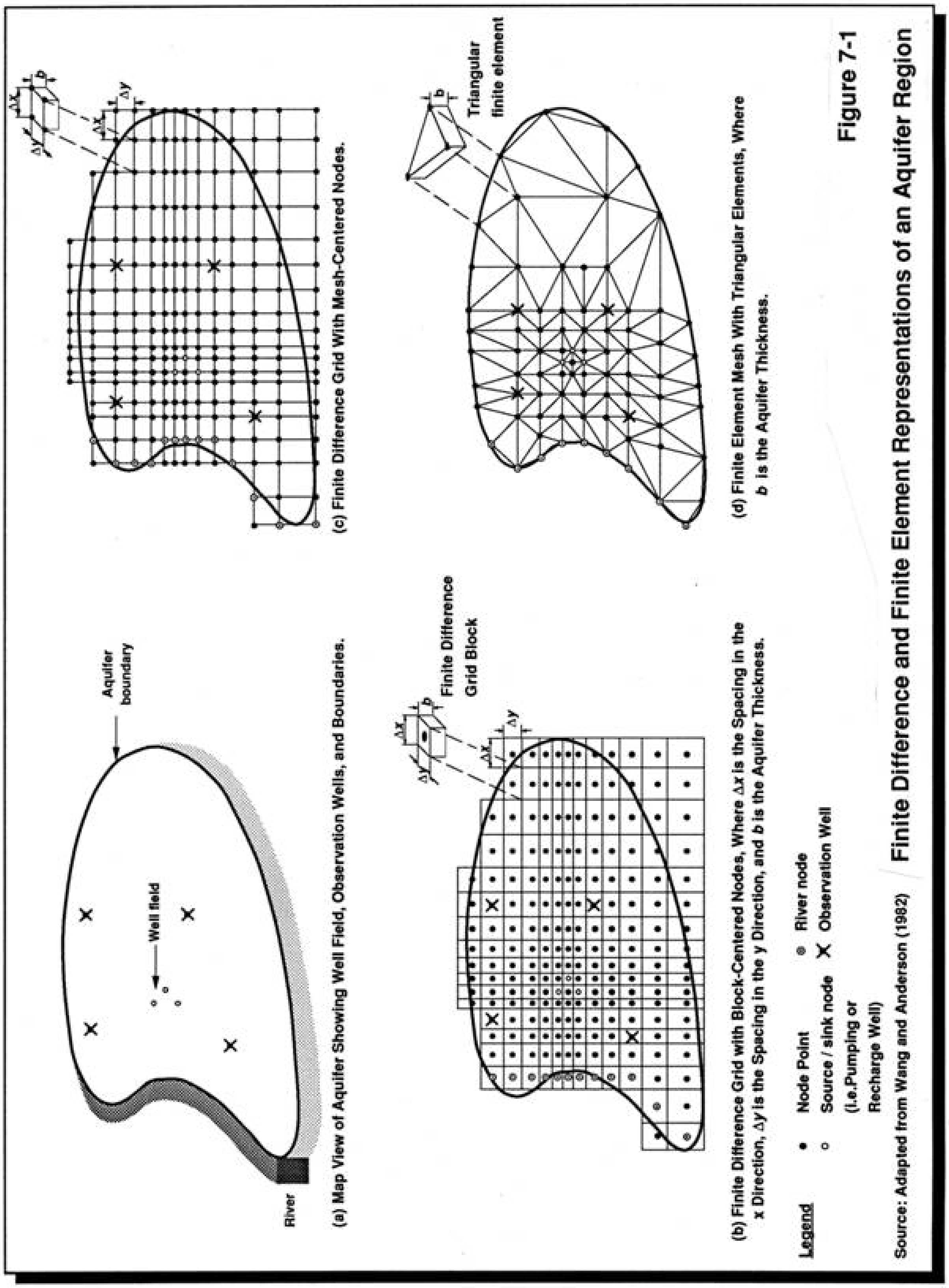
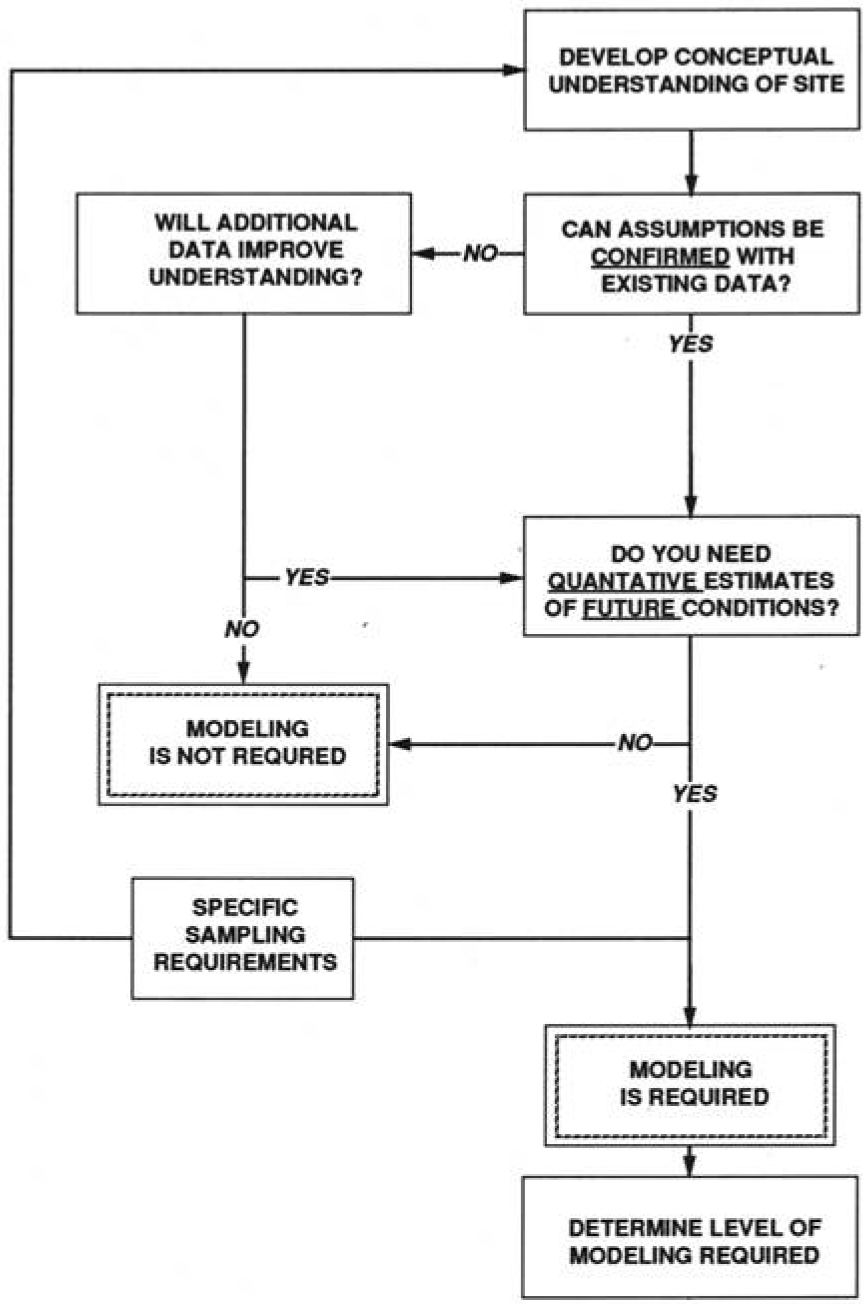


Figure 7-1
Finite Difference and Finite Element Representations of an Aquifer Region



Adapted from: Mercer and Faust (1981)

Figure 7-2

Flow Chart to Determine if Modeling is Required

TABLE 7-1

Natural Processes That Affect
Subsurface Contaminant Transport
(after Keely, 1987)

PHYSICAL PROCESSES

- Advection
- Hydrodynamic Dispersion
- Molecular Diffusion
- Density Stratification
- Immiscible Phase Flow
- Fractured Media Flow
- Thermally Driven Flow

CHEMICAL PROCESSES

- Oxidation-Reduction Reactions
- Radionuclide Decay
- Ion-Exchange
- Complexation
- Co-Solvation
- Immiscible Phase Partitioning
- Sorption
- Hydrolysis
- Precipitation/Dissolution

BIOLOGICAL PROCESSES

- Microbial Population Dynamics
- Substrate Utilization
- Biotransformation
- Adaptation
- Co-metabolism

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 8.1 INTRODUCTION

SECTION 8.1
INTRODUCTION

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8.1 INTRODUCTION

A geophysical survey is an indirect method of determining the state of the subsurface in the survey area. By indirect, it is meant that the geophysical survey measures some physical property of the subsurface and uses the results to infer the material that caused it. Like a blind person trying to identify an object without the benefit of sight, the geophysicist cannot directly observe the subsurface but must instead rely on other, less direct methods of data collection to make his/her determination as to its state. Variations in the electrical field (applied and ambient), gravity and magnetic potentials, and seismic wave velocities, amplitudes and frequencies are systematically measured to infer the structure and composition of the subsurface soil, rocks and groundwater. Many geophysical methods produce results, which by themselves, cannot provide a definitive characterization of subsurface conditions; however, by using a combination of geophysical techniques (each of which measures a different physical property of the earth), the geophysicist can often eliminate incorrect possibilities to arrive at a correct interpretation.

The usefulness of geophysical techniques for site characterization and the evaluation of contaminated sites have been well established during the past two decades. Determination of depths to both bedrock and the water table are routinely performed. Geophysical techniques are also used with great success to locate buried metal objects (barrels, tanks, pipes, trucks), certain migrating contaminant plumes, debris-filled trenches, determine the integrity of "cut off" slurry trenches, and trace the migration of contaminants through fractured bedrock.

Geophysical investigations in environmental studies are best used to:

- Characterize geologic conditions
- Determine the source and extent of contamination problems
- Optimize test pit and boring locations

In many cases, the proper application of a geophysical investigation adds significant information and reduces the costs necessary to acquire the information required to determine effective site remediation and cleanup. The correlation of geophysical data methods, with borehole geologic and sampling data will usually provide the most meaningful results.

The physical characteristics of a site which geophysics can help determine include: characterization of the types of overburden materials and thickness, as well as soil classification and permeability characterization of the types of bedrock and depth to bedrock; characterization of water table elevations, hydraulic gradients, groundwater flow direction; and identification and characterization of all other physical site characteristics such as buried utility lines, sewers, and water mains.

In certain instances, geophysics can also be used to help identify the source and extent of release of contaminants by helping to establish: the source(s) of releases of oil or hazardous material; the horizontal and vertical extent and (relative) concentrations of certain oil or hazardous materials in some media; the estimated volume of contaminated soil and (ground) water; some of the existing and potential soil and groundwater pathways; and the existence of certain plume(s) of oil or hazardous materials (ie,

containing dissolved ionic contaminants) in the groundwater and the potential migration of the plume.

It should be noted that results of geophysical site investigations alone, rarely provide complete answers to the data requirements of an environmental investigation. An intrusive (e.g., soil boring) program is usually necessary to supplement a geophysical program. Results of the geophysical program, however, can minimize the number of borings necessary by optimizing their placement. In return, the borings provide important data that can be used to refine geophysical interpretations and results. Geophysical methods can provide accurate and inexpensive (in comparison with conventional intrusive techniques) measurements of average subsurface conditions over large areas, while borings provide detailed information for a limited area. A combined geophysical survey/boring program is therefore often the most cost-effective system for the complete analysis of site conditions.

8.1-1 Document Structure

This document has been divided into 3 sections and are as follows:

- o 8.I Introduction
- o 8.2 Synopsis of Geophysical Investigation Methods
- o 8.3 Borehole Geophysical Methods

Section 8.2 is a synopsis of the geophysical techniques (excluding marine geophysical methods), which are covered in greater detail in the MADEP publication: Standard References for Geophysical Investigations.

The entire Chapter 10 of the Standard References for Geophysical Investigations (WSC 94-311) has been included as Section 8.3 of this document. Chapter 10 was included in its entirety to increase the utility of this document as a reference document, since this chapter covers the suite of geophysical techniques that are commonly used in the investigation of subsurface conditions using soil borings and monitoring wells as measurement media.

8.1-2 Background Reference Materials

The reader is referred to the 1994 MADEP Publication: Standard References for Geophysical Investigations, WSC 94-311, for a more complete explanation of the methods briefly described in the following section. A comprehensive discussion of geophysical methods and their application to groundwater problems is included in the 1985 Electric Power Research Institute's Groundwater Manual for the Electric Utility Industry, Volume 3, Groundwater Investigation and Mitigation Techniques, Section 3.

Another useful document providing a broad non-technical overview is a compilation entitled "Geophysical Techniques for Sensing Buried Waste and Waste Migration," by Benson et al. (1987). Additional sources of information for specific methods are referenced in the discussions of each geophysical method. Texts that generally discuss the applicable geophysical techniques include Dobrin (1976), Telford et al. (1976, Mooney (1977), U.S. Army Corps of Engineers (1979), Grant and West (1965), and Griffiths and King (1981).

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STANDARD REFERENCES FOR MONITORING WELLS

SECTION 8.2 SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

SECTION 8.2
SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

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8.2 SYNOPSIS OF GEOPHYSICAL INVESTIGATION METHODS

The following are synopses of the geophysical methods described in the MADEP publication entitled: Standard References for Geophysical Investigations, WSC 94-311. This section and the accompanying Table 8.2-1 offer a brief overview of the various methods. The reader is encouraged to consult the aforementioned publication for a more detailed discussion of the methodologies.

8.2-1 SEISMIC METHODS

8.2-1.1 Operating Principle

The seismic methods of geophysical exploration are active (manmade energy sources are used) techniques used to characterize subsurface geology. These methods are an indirect means of determining the type and thicknesses of the various materials underlying a site. The general principle of seismic surveying is that dissimilar subsurface materials can be determined by the differences in their respective physical properties. Each material has a unique set of physical properties, which affect the amplitude and velocity of seismic waves traveling through them. Seismic surveys are conducted by inducing seismic energy into the subsurface and measuring the resultant velocity and amplitude of the seismic waves by detectors located on the ground surface. The resultant data can be used to infer the types of material present in the subsurface.

There are two basic methods of seismic surveying: reflection and refraction. The basic methodology for these seismic techniques consists of actively generating waves in the ground and detecting them at ground surface after they have either reflected or refracted off of subsurface layers. The energy (seismic waves) is generated by various means such as weight drops, explosives, mechanical sources, sledge hammers, etc.

Electromechanical transducers (which turn ground motion into electricity), called geophones, are used to detect the arrival time and amplitude of the induced ground motion. Arrays of geophones, called seismic spreads, are connected by electrically conductive cables to the seismograph, which processes and records the collected data. Recordings are made with either analog or digital seismographs. Preliminary data evaluation can usually be performed in the field with analog recordings. Playbacks of digital recordings are performed in the office for final data processing and report preparations.

Seismic refraction is by far the most prevalent method used in the shallow subsurface studies (less than 300 feet) employed during environmental investigations in Massachusetts and New England.

8.2-1.2 Applications

Seismic refraction surveys can be employed to: delineate the types and thicknesses of geologic materials; determine depth to groundwater; correlate stratigraphy across a study area (in conjunction with test pit and/or boring log data); detect sinkholes and cavities; detect bedrock fracture zones; determine extent of landfills; and determine extent of filled areas such as reclaimed quarries.

When a seismic refraction survey is performed prior to an intrusive field investigation, the data can be used to help determine the number, distribution, and depth of test pits, borings, and monitoring wells.

When a seismic refraction survey is performed after intrusive field investigation, the use of physical data to calibrate refraction data allows the interpolation of subsurface conditions across large areas with a great degree of confidence. Intrusive field data can also be used to refine the interpretations of seismic data, which had been collected prior to the start of the intrusive field program.

For larger investigations, especially those that require the delineation of bedrock competence and topography (DNAPL investigations), the combined use of seismic refraction with conventional investigative techniques can often result in a higher level of data volume and quality, while providing a considerable savings of time and money for the project.

8.2-1.3 Limitations

Seismic refraction does have limitations. The first is cost. Seismic refraction surveys cost between $2,000 and $4,000 per day. For smaller investigations, which might only require the installation of a few soil borings and water table monitoring wells, it probably would not prove cost effective to employ seismic refraction. Seismic refraction surveys by nature are sensitive to ground vibrations. Unfortunately, many human activities, including vehicle traffic, construction, and manufacturing, can create noise (unwanted ground vibrations) which can make collection of wanted data in a particular area difficult if not impossible. Seismic refraction surveying is seasonal. Frozen ground conditions make data collection difficult if not impossible. Interpretation of seismic refraction data is often non-unique. Some measured velocity values readily correlate with specific geologic materials such as massive, intact bedrock. Other velocity values, however, do not correspond to a unique interpretation of the nature of the materials surveyed and require correlation with soil borings or test pits for exact determination of the conditions and types of geologic layering.

8.2-2 RESISTIVITY METHOD

8.2-2-1 Operating Principle

Electrical resistivity surveying is an active geophysical technique that involves applying an electrical current to the earth and measuring the subsequent electrical response at the ground surface in order to determine physical properties of subsurface materials. The general principle of resistivity testing is that dissimilar subsurface materials can be identified by the differences in their respective electrical potentials. Differences in electrical potentials of materials are determined by the application of a known amount of electric current to these materials and the measurement of the induced voltage potentials. Ohm's law states that the voltage (V) of an electric circuit is equal to the electric current (I) times the resistivity (R) of the medium (V-IR). Resistivity surveys are conducted by: 1) applying a known amount of electric current (I) to the earth; 2) measuring the induced voltage (V) ; and, using these two measurements, 3) determining the resistivity (R) of the volume of earth being surveyed.

Resistivity methods usually require that both current inducing and measurement electrodes to be pushed or driven into the ground. With connecting wires from the instruments to the electrodes, electrical current is introduced into the ground using the current electrodes and resistivity measurements are performed using different measurement electrode configurations and spacings. There are a number of standardized testing procedures, some of which are described in detail in this section.

Resistivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer that exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i.e., salinities) will appear to be more than one geoelectric layer. The interpretation of resistivity data is therefore best made in conjunction with other geophysical techniques (i.e., seismic refraction) or conventional subsurface investigations (i.e., soil borings).

8.2-2.2 Applications

Historically, resistivity surveys have been used for a number of geologic mapping objectives, including groundwater detection, sand and gravel mapping, bedrock depth determination, and other classic geologic exploration exercises. At present, these methods are commonly used to evaluate subsurface conditions as they relate to hazardous waste issues.

Resistivity measurements are commonly used to delineate either changes in resistivity with depth or lateral variations in resistivity. These applications are known respectively as:

- o Vertical electrical soundings (VES)
- o Horizontal profiling

VES surveys, which determine vertical resistivity changes, employ variable electrode spacings. VES surveys are used to identify geoelectrical layering in soil and rock. These data are often used to identify: the groundwater table; clay layers; the bedrock surface; and to select optimum electrode spacings for horizontal profiling surveys.

For horizontal profiling, which determines lateral resistivity changes at a fixed depth of investigation, the current measurement electrode spacings are kept constant. Horizontal profiling is used to identify lateral resistivity variations in a survey area. Horizontal profiling can be used to detect conductive groundwater plumes (ie landfill leachate), landfill limits, geologic contacts, and sink holes (often present in limestone lithology).

Electromagnetic induction (EM) survey methods have generally supplanted resistivity surveys as the method of choice for shallow horizontal resistivity profiling because of EM's ease of use and increased data collection speed. Resistivity methods, however, provide better vertical resolution and are therefore superior to most EM methods for vertical resistivity profiling and for deeper horizontal resistivity profiling. Resistivity may

also be applicable at sites where interferences from surface metal objects (e.g., fences) and/or power lines make the use of EM surveys impractical.

8-2-2.3 Limitations

Resistivity surveying methods can be carried out only in media that are neither extraordinarily conductive nor resistive. Cultural interference (from powerlines, pipelines, and metal fences) is another serious limitation of resistivity surveying. Thin layers, or targets of limited lateral extent, may be undetectable because the measured potentials integrate the effects of a large volume of material. Because this technique measures geoelectric layers rather than geologic ones, the solution is non-unique. Therefore, in the absence of correlating data (e.g. boring logs) incorrect stratigraphic conclusions can be drawn. Differentiation between highly conductive materials (i.e., clay or salt water versus contamination plumes) may not be possible. A resistivity horizontal profiling survey is more labor intensive and time consuming than an EM survey.

8.2-3 SELF-POTENTIAL METHOD

8-2-3. 1 Operating Principle

The self-potential (SP) survey method is a passive geophysical technique that measures extremely small, naturally occurring voltage variations in the earth. The technique is based on the observation that when certain materials are in contact with either a different material (e.g., buried iron next to buried copper) or a localized change in the condition of the same material (e.g., interface of saturated and unsaturated condition), an electrical current is created. This current is readily detectable with inexpensive, portable voltage measuring instrumentation.

The technique is simple to operate, consisting of a series of measurements of electric potential (voltage) across two electrodes that are in contact with the ground and spaced at varying distances.

8.2-3.2 Applications

The most relevant application of this method to environmental investigations is the tracing of shallow leachate seepage zones when such zones are known to exist.

8.2-3.3 Limitations

Given the small size of the naturally occurring voltage differentials (measured in thousandths of volts), the SP method is extremely sensitive to man-made electrical interferences.

Although the technique is receiving increased attention for groundwater contamination assessment, the reliability and applicability of this methodology are inconclusive at this time.

8.2-4 ELECTROMAGNETIC INDUCTION METHOD

8.2-4.1 Overview

Electromagnetic Induction (EM) methods are non-destructive geophysical techniques for measuring the apparent conductivity of subsurface materials. As with resistivity surveys, the general principal of EM surveys is that dissimilar subsurface materials can be identified by the differences in their respective electrical responses to the introduction of an electrical stimulus. There are two basic types of EM surveys, terrain conductivity and Very Long Frequency (VLF). Each survey method is explained below. Terrain conductivity, given its broader applicability and usage in environmental studies, is explained in greater detail.

8-2-4.1.1 Terrain Conductivity - Operating Principle

Terrain conductivity surveys employ the same operating principals as conventional resistivity surveys (Section 4), but differ from a resistivity survey in the manner with which an electrical stimulus is introduced to the earth. The terrain conductivity method of EM surveying is an active geophysical technique that involves "inducing" an electric current in the subsurface and measuring the subsequent electrical response at the ground surface to characterize the physical properties of subsurface materials. In contrast, resistivity surveys directly apply an electrical current to the ground using current electrodes and measure the resultant voltage potential using measurement electrodes. The resistivity method requires that electrodes are driven into the ground and connected with wires at each survey point. Terrain conductivity surveys employ a transmitting coil, which is not directly coupled to the earth, to remotely induce a voltage potential in the ground and a remote receiving coil to measure a secondary current created by the effect of the induced voltage in a conductive medium.

The name "terrain conductivity" stems from the different manner (with respect to resistivity surveys) with which terrain conductivity measures the electrical properties of the materials investigated. The resistivity method directly applies a current (I) to the ground, measures the resultant voltage (V), and calculates the resistivity (R) of the material measured (given that V=IR). Terrain conductivity surveys use a known current (I), passed through a transmitting coil to create an electromagnetic field which induces a voltage (V) in the ground. If the ground material is conductive, then a secondary (induced) electromagnetic field will be created. The terrain conductivity receiving coil measures the currents (I) created by the primary (transmitted) electromagnetic field and the secondary (induced) electromagnetic field. The ratio of these two currents is proportional to the conductivity (which is the inverse of resistivity, R) of the material being surveyed. (A more complete explanation of the inductive measurement theory is presented below in the Introduction.)

Terrain conductivity surveys identify geoelectric layers rather than geologic ones. A geoelectric layer is a layer that exhibits a similar electric resistivity response. A geoelectric layer can, but does not always, correspond to a geologic one. For example, an isotropic homogeneous sand, which is saturated with a fluid exhibiting a single conductivity response, will appear to be a single geoelectric layer. The same sand, if filled with fluid layers containing different conductivities, (i.e. salinities) will appear to be more than one geoelectric layer. The interpretation of terrain conductivity data is therefore best made in conjunction with other geophysical techniques (i.e., seismic refraction) or conventional subsurface investigations (i.e., soil borings).

8-2-4.1.2 Terrain Conductivity Applications

Common applications for terrain conductivity surveys include: conductive contaminant plume mapping; locating buried metallic objects and identifying landfill boundaries.

EM measurements are commonly used to delineate either changes in conductivity with depth or lateral variations in resistivity. These applications are known respectively as:

- Vertical electrical soundings (VES)
- Horizontal profiling

VES surveys, which determine vertical conductivity changes, are best conducted with instruments that allow variable coil spacings (e.g., Geonics EM 34). A limited (by depth of investigation) VES survey can also be conducted using a fixed coil spacing instrument (e.g., Geonics EM-31) by altering the orientation (turning on its side) of the measuring equipment. VES surveys are used to identify geoelectrical layering in soil and rock. These data are often used to identify the groundwater table, clay layers, and the bedrock surface.

For horizontal profiling, which determines lateral resistivity changes at a fixed depth of investigation, the current measurement coil spacings are kept constant. A fixed coil spacing instrument can be operated by one person and is well suited for horizontal profiling. Horizontal profiling is used to identify lateral resistivity variations in a survey area. Horizontal profiling can be used to detect conductive groundwater plumes, landfill limits, geologic contacts, and sink holes (often present in limestone lithology).

As with other geophysical techniques, the effectiveness of terrain conductivity interpretation is increased by correlation with other geophysical techniques. For example, the combination of terrain conductivity and magnetometry surveys (Section 8) is ideal for a combination of location of buried drums, while the combined use of terrain conductivity and seismic surveys (Section 3) will effectively differentiate between conductive contaminant plumes and landfill boundaries.

The terrain conductivity survey method is non intrusive and can be conducted at a more rapid pace (and less expensively) than conventional resistivity surveys. The portable instrument requires only a one or two person field party. Measured conductivity values can be observed during data acquisition, and yield immediate preliminary information for an experienced operator. For this reason, terrain conductivity survey methods have generally supplemented resistivity surveys as the method of choice for shallow horizontal profiling of the subsurface.

8-2-4.1.3 <u>Terrain Conductivity Limitations</u>

Limitations of the terrain conductivity method include the following. The instrument is effective for only a limited dynamic range (1 to 1,0-00 millimho/meter) of soil and conductivities. Terrain conductivity is sensitive to the presence of other EM fields, such as those associated with power lines and/or the presence of highly conductive objects, such as metal fences. Terrain conductivity has less vertical resolution than conventional resistivity surveys. The limited strength of the terrain conductivity transmitter signal, due to battery and coil size constraints (a compromise to portability), limits the instrument penetration to shallower depths that conventional resistivity surveys. Even simple stratigraphic layering cannot be distinguished without complex application and interpretation.

8.2-4.1.4 <u>VLF - Operating Principle</u>

The VLF survey method is an EM prospecting technique based on the principle of radio wave transmission and reception. The VLF method does not employ an operator induced electromagnetic field, but instead utilizes low frequency transmissions from a submarine communications network established and maintained by the U.S. Navy as a power source.

VLF signals are transmitted by vertical radio antennae several hundred feet high with signal outputs ranging from 300 to 1,000 kWatts. The effective range of these transmitters as a VLF survey power source is on the order of thousands of miles. (It should be noted that a site must be a minimum of 50 miles from a transmitter for this technique to be effective.) A worldwide network of VLF stations has been established in such varied locations as Bordeaux. France (15.1 kHz), Moscow, USSR (17.1 kHz), and Cutler, Maine (24.0 kHz).

The field emitted by VLF antennae is horizontal, and its magnetic lines comprise concentric rings that "ripple" out from the transmitter. When this magnetic field encounters an electrically conductive structure on the surface or underground, weak secondary currents are generated around the structure. These currents create a secondary magnetic field.

VLF can detect long conductors such as electric cables, pipelines, and certain bedrock fractures. In order for the VLF method to be effective in detecting underground geologic structures, the structure must have: 1) the direction of its long axis within 30 degrees relative to a line tangent to the concentric rings that "ripple" from the transmitter (to initiate induction); 2) minimum dimensions of approximately 50 meters in length, 10 meters in depth, and about one meter in thickness; 3) a dip angle not less than 30 degrees from horizontal; and 4) higher electrical conductivity than the surrounding material.

Unlike terrain conductivity, the depth of VLF penetration is not a function of coil spacing, but rather the resistivity of the materials surveyed. Depth of penetration of VLF signals is directly proportional to (varies by approximately four times the square root of) the material's resistivity. For example, VLF signals propagating through granite (a highly resistive material) can penetrate to depths greater than 300 meters. However, a material such as salt water may limit depth of penetration to one to five meters.

8.2-4.1.5 VLF - Applications

The VLF receiver measures the current density due to the primary (transmitted) and secondary (induced) magnetic fields. From these measurements, structures such as water-saturated fracture zones, metallic ore bodies, mineralized zones, and long conductors such as electric cables or pipelines may be detected. The ability to detect water-filled bedrock fracture zones makes this type of survey method useful for bedrock water supply development and for site investigations that involve bedrock contamination.

8.2-4.1.6 VLF – Disadvantages

The VLF survey operator has no control over power source - VLF transmitters are sometimes turned off for maintenance. Even when the transmitters are operating, the orientation (both strike and dip) of the object surveyed to the power source (which the operator also has no control over) will affect the success of the survey.

VLF data interpretation is difficult - VLF data does not provide data that can be directly related to subsurface conductivity. Interpretation is more subjective and therefore relies heavily on operator experience.

VLF survey limitations are: susceptibility to surface anthropogenic interferences (e.g., fences, automobiles, power lines). The effective depth of VLF investigation is extremely reduced in areas that contain shallow material of high conductivity.

8.2-5 GROUND PENETRATING RADAR (GPR)

8.2-5.1 Operating Principle

Ground penetrating radar (GPR) is an active geophysical system that transmits high frequency (80-1,000 MHz) electromagnetic waves (radar energy) into the ground and records the energy reflected back to the surface. It is a reflection technique similar to the single-trace seismic reflection method commonly used in marine subbottom profiling. The two techniques differ in that the seismic method uses audio frequency sound waves, while the radar method uses electromagnetic waves.

GPR is a continuous profiling method that transmits radar energy into the ground and records the radar energy reflected back by subsurface objects or layers. GPR is useful when a rapid survey with detailed vertical and horizontal control is desired. A GPR survey produces a graphic cross-sectional view of earth stratigraphy and targets (i.e., drums, pipelines, utilities, boulders, etc.) below the ground surface. Under optimum conditions, this method can be effective to depths of 70 feet (using commercially available equipment), although depth penetration is core often limited to the range of ten feet or less below ground surface.

8.2-5.2 Applications

GPR has been used to locate: underground storage tanks; underground pipes; buried drums; buried foundations; voids in rock and concrete; buried archaeological artifacts, excavations, filled pits and lagoons, and numerous other site specific applications and lithologic contacts. GPR can also be used to determine: stratigraphy; depth to the water table; and depth to bedrock. GPR has also been successfully used to delineate the lateral extent of contaminant plumes.

8.2-5.3 GPR Limitations

The limitations of GPR include the following. GPR survey lines must be cleared to ground level (e.g., may require cutting of brush and/or removal of obstructions). The depth of GPR signal penetration is highly dependent on the materials present beneath the survey area (signal penetration in a saturated clay layer may be only a few inches). GPR interpretations are subjective, often requiring data corroboration using other geophysical methods and/or verification with borings or test pits.

To maximize resolution and minimize scattering losses, survey lines must be as smooth as possible to prevent bouncing and jarring the radar antenna. Survey lines cleared of debris also allow the antenna to be pulled at an even, continuous pace, permitting the easy determination of horizontal scale.

The depth of GPR investigation at a site is limited by soil type and/or the presence of high "loss" materials. Penetration of up to 75 feet has been reported for water-saturated, clean sands in a Massachusetts glacial delta using a commercial antenna. Signal penetration in saturated clays, on the other hand, is on the order of magnitude of only a few inches. In New England, the presence of glacial tills, and lacustrine and marine clays limit the depth of penetration. Delineation of materials beneath a conductive layer may also not be possible.

8.2-6 MAGNETIC METHODS

8.2-6.1 Overview

Magnetic surveying is a passive geophysical technique that measures the strength of the total magnetic field at any given point on the earth. The purpose of the magnetic survey in environmental investigations is to detect magnetic anomalies (variations in the expected field), which can be attributed to the presence of buried iron or steel objects. Magnetic surveys can also be used to locate bedrock fracture zones due to the fact that the hematite in fracture zones weathers to limonite, causing a change in magnetic signature.

Magnetism can be "induced" into materials that have a high magnetic susceptibility. Magnetic susceptibility is defined as the ability of a material to acquire a magnetization in the presence of a magnetic field (in this case the Earth's). The magnetic field induced is dependent upon the geometry, orientation, and magnetic properties of body, and the direction and intensity of the Earth's field. In order to recognize a magnetic anomaly, it must be several times larger than the background noise level along that profile.

Iron and steel (ferrous) objects have a high susceptibility and are therefore compatible with detection by magnetic survey methods. Buried ferrous metal objects such as steel drums or tanks cause local variations or anomalies in the earth's magnetic field that can be detected by a magnetometer. The size (amplitude) of this perturbation caused by the object is related to a number of factors such as the size of, distance to, and intensity of magnetization of the buried object.

Other non-ferrous metals, such as brass, copper, and aluminum, have low magnetic susceptibility and, therefore, will not be detected by a magnetic survey.

An instrument called a magnetometer is used in the performance of magnetic surveys. The magnetometer is used to determine the direction, gradient, and intensity of the total magnetic field. Various forms of magnetometers are used in land, airborne and marine type operations. The land instruments are lightweight and portable, and measurements are readily accomplished by a one- or two-person field party.

8-2-6.2 Applications

Magnetic surveys, performed as part of environmental investigations, are nearly always used to detect induced magnetism in iron and steel objects such as buried drums, pipelines, and underground storage tanks (USTs). The results of magnetic surveying can be used to direct excavation activities of buried drums and USTs.

The results can also be used to direct the placement of both upgradient and downgradient monitoring wells (in conjunction with data regarding the known or inferred direction of groundwater flow) to facilitate the assessment of potential releases of contaminants from these objects on water quality.

Magnetic surveys utilizing portable field magnetometers are relatively easy to perform and are usually the easiest to interpret with regard to siting drilling locations. Magnetic surveys, however, are susceptible to interferences from manmade structures such as utilities, buildings, and fences.

8-2-6.3 Limitations

Limitations of the magnetic survey method include the following. A magnetometer is susceptible to the interferences associated with the presence of other magnetic fields, such as those associated with power lines. Also, since the strength of the induced magnetic field is a function of the susceptibility of the material surveyed, the presence of highly susceptible objects, such as metal fences, also creates unwanted interferences. An anomaly of interest must be several times larger than the background noise (e.g., metal fences, remnant magnetism) to be detected. Interpretation is non-unique given the inherent complexity of dipole behavior and the fact that a number of different types and configurations of sources can cause the same anomaly.

8.2-7 GRAVITY METHOD

8.2-7.1 Overview

The gravity survey method is a passive geophysical technique that measures extremely small variations in the earth's gravitational field using a highly sensitive instrument. In gravity exploration the variation in density of the surveyed area is the only significant factor. Lateral variations in the distribution of mass in the earth's crust produce distortions or differences in the gravitational field. Tectonics, faulting, erosion, deposition, and other geologic movement involving rock often result in lateral density variations in the subsurface rocks. Measured gravitational differences are interpreted in terms of probable subsurface mass distributions, which are inferred from surface and near surface geologic conditions.

8.2-7.2 Applications

The "microgravity" survey method produces data that allows more detailed or higher resolution interpretation than ordinary gravimetric measurements taken on a regional scale.

Microgravity measurements can be used to detect the following conditions: joint and fracture zones; dissolutions; collapses: cavities; buried river channels; and fault scarps. The detailed resolution of the microgravity survey is more suited to the limited areal surveys associated with environmental investigations and may be useful to characterize sites prior to drilling test wells.

The advantages of a gravity survey are that field work can be carried out by one to three persons in any accessible area, including highly developed urban and industrialized sites, over pavements, fills, landfills, on lake ice, and inside buildings. Instrumentation is portable; the work can be silent and produce no visible disturbance to an environment other than stakes or other station markings. The method lends itself well to areal coverage; contour maps of bedrock or other features have obvious advantages over information at points or along profiles.

8.2-7.3 Limitations

The sensitivity of the "Microgravity" instrumentation creates logistical problems including: a greater need for more detailed elevation data; a "quiet" site with regard to background vibrations that might affect the microgravimeter; as well as some inherent stability problems for the instrument itself.

The other limitations of a gravity survey are that: applications are limited to mapping of density-dependent interfaces; accurate station locations and elevations are necessary; calibration with geological "knowns" such as outcrops, borings, or seismic profiles is necessary for quantitative work; and excessive topography, access problems, and certain bedrock complexities may seriously limit the accuracy of data interpretation.

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COMPARISON OF GEOPHYSICAL METHODS FOR HAZARDOUS WASTE APPLICATION

Geophysical Method	General Applications	Advantages	Limitations	Relative Cost	Depth of Investigation
Seismic Refraction	Determine the depths to bedrock, water table, glacial tills. Identify zones of fractured weathered bedrock. Accuracy ±10% of depth to interface.	Accurately identifies soil and rock layering as reflected by contrasts in seismic compressional wave velocity values.	Does not detect contaminants in ground water. Sensitive to vibration, construction activities and electrical noise. Frozen ground precludes use of geophones and shot points.	Moderate to high	Shallow (0-10m) and deep (10-100+m)
Electrical Resistivity	Determine depth to water table, clays, bedrock, etc. Accuracy ±25% of total depth. Identify highly conductive or resistive contamination plumes.	Equipment is inexpensive, easy to operate. Rapid method for determining ground resistivity layering.	Interpretation is not unique. sensitive to fences, power lines, pipes, and other metal objects. Dipping strata complicates interpretation.	Moderate	Shallow (0-10m) and deep (10-100+m)
Self-Potential	Identify ground water flow and area of contamination.	Equipment is inexpensive and easy to operate.	Highly qualitative interpretation. Susceptible to interference due to lithological and vegetation changes.	Inexpensive	Shallow (0-20m)
Electromagnetic Induction	Plume detection and tracing. Depths to water table, bedrock, clays, etc. Accuracy approximately ±25%.	Walk-over method of determining ground conductivity	Lacks the vertical resolution and depth penetration of resistivity.	Moderate	Shallow (0-5m) and deep (5-60m)
Ground Penetrating Radar	Buried metal detection and general identification (drum, tank, debris, etc.). Accuracy ±20%. Filled trench identification.	Tow-along method, equipment is commercially available, easy to operate, high resolution.	Depth of penetration limited by conductivity of material. Sensitive to shallow lithologic changes. Highly qualitative interpertation.	Moderate	Shallow (0-10m)
Magnetics	Buried (ferrous) detection.	Walk-over method, equipment easy to operate, commercially available. Rapid method for metal (ferrous) detection.	Sensitive to metal fences, power lines, pipes, and cultural metal ferrous objects.	Inexpensive	Shallow (0-10m) and deep (10-100+m)
Gravity	Detection of fault scarps, buried river channels, cavities, and collapse or fill areas.	Field work conducted by one person, data can be acquired in highly developed urban areas, equipment is portable.	Interpretations not unique. Geologic data necessary for interpretation, highly trained experienced field personnel, instrument and survey support expensive.	High	Deep (10-100+m)
Borehole	Determine stratigraphy, fracture zones, porosity, permeability.	Known depth of measurement. Little data reduction needed. Rapid, most equipment easy to operate. Very good vertical resolution.	Limited lateral extent. Radioactive tools need special licensing. Borehole construction may limit techniques.	Low to Moderate	Not Applicable

*All methods can be operated in a non-intrusive manner.

Table 8.2-1

Comparison of Geophysical Methods for Hazardous Waste Applications

COMMONWEALTH OF MASSACHUSETTS

DEPARTMENT OF ENVIRONMENTAL PROTECTION

STANDARD REFERENCES FOR MONITORING WELLS

SECTION 8.3 BOREHOLE GEOPHYSICAL METHODS

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8.3 BOREHOLE GEOPHYSICAL METHODS

8.3-1. OVERVIEW

Borehole geophysical surveys are designed to provide a continuous vertical profile of the soil, rock and water conditions immediately adjacent to the borehole. Logging is accomplished by lowering probes into the borehole to measure the electrical, acoustical, or radioactive properties of the materials surrounding a borehole. The surveys are non-destructive and can often be run in existing boreholes, monitoring wells, and water wells with no modifications.

Borehole geophysical methods are used primarily to characterize rocks, correlate overburden or rock units, and determine physical and hydrologic properties. Table 8.3-1 provides a listing of the applications for the methods described in this section. Specific applications include determining porosity, locating clay layers, determining water quality, estimating permeability, and finding fracture zones and zones of water loss or gain. More detailed discussion of the theory and interpretation of the use of borehole geophysical methods in groundwater investigations is presented by Keys and MacCary (1971), Kwader (1982), and Collier and Alger (1988).

The primary advantage of borehole methods is that they provide an unbiased, high density of measurements of soil, rock and water properties at precise depths. Borehole methods are fast and generally unaffected by surface features such as power lines, buildings and railroad tracks. Little data reduction is necessary before most logs can be interpreted; often, preliminary interpretations can be made as they are being run. Borehole logging is non-destructive and can often be run with no modifications in existing cased or uncased boreholes and in the screened and unscreened intervals of monitoring wells.

Some borehole methods, such as the temperature log (a log is the printed display of the parameter being measured vs. the depth where the measurement is taken), the caliper log, and the flowmeter log are relatively simple to operate and the data recordings are easy to interpret.

Other methods, such as logging with an active nuclear source and resistivity logging are much more complex for operation and/or for data interpretation. Borehole geophysical logging using such methods is a technical specialty that requires complex electronic equipment to be operated according to exact design specifications. Since no two boreholes exhibit the same geophysical response, and as responses can not be quantitatively validated during logging, the quality of a log depends strongly on the operator's experience and judgment.

The radius of investigation for most probes is commonly less than one foot. Depending on the permeability of the formation and the drilling techniques applied, the condition of materials investigated may be altered by the drilling method. The borehole surveys may therefore provide only limited representation of true formation properties.

Borehole geophysical methods may not be cost-effective for typical environmental investigations in Massachusetts, where shallow overburden wells dominate. Borehole geophysical methods are best suited for deep bedrock wells, where the information gathered will be most useful. When natural in-situ conditions are present, and several deep boreholes are logged and correlated, often very large areas can be geologically characterized with a minimum of time and cost.

8.3-2 INTRODUCTION

Borehole geophysical techniques (also called logging) are a group of active and passive geophysical methods used to provide detailed physical properties of soil, rock, and water. The term "active" implies subjecting the area around and in the borehole to a stress (either electric, thermal, acoustic, etc.) in which a response can be measured (formation-penetrating methods), while "passive" involves measuring only naturally occurring conditions (non-penetrating methods).

Table 8.3-1 shows the array of available borehole techniques keyed to types of subsurface information desired and limitations posed by borehole conditions. Many of the techniques are based on counterpart surface geophysical methods, adapted to the borehole environment. Typically, these adaptations include the reduction of equipment size (the probes for most techniques will fit inside a 2-inch diameter hole), reduction and standardization of the fixed source to receiver spacing (and sometimes a corresponding reduction in the depth of investigation), protection of probes from pressure and temperature effects, and interpretation of data with respect to vertical rather than horizontal changes.

Borehole geophysical logging methods to be discussed are:

- o Downhole television camera
- o Caliper
- o Temperature
- o Electrical methods (Single-point-resistance, Normal resistivity, SP, Fluid resistivity, Electromagnetic/Induction)
- o Flowmeter
- o Acoustic methods (Velocity. Waveform, Acoustic televiewer)
- o Nuclear methods (Natural gamma. Neutron, Gamma-gamma)
- o Vertical seismic profiling

Use of more than one logging technique is generally necessary to determine soil and water properties adjacent to the borehole. Because each probe has a different response, these logs are interpreted by cross-comparisons to determine specific characteristics of interest. For example, caliper, single-point resistance, acoustic and thermal logs may be run as a suite to identify fracture zones in rock.

8.3-2.1 Equipment

Figure 8.3-1 shows a typical geophysical logging set up. The surface and downhole equipment used in borehole geophysical surveys is connected by the logging cable. The cable provides transmission of electrical power to the downhole probe and a return path for signals generated in the probe. Cables are usually one- or four-conductor, insulated, wire-wrapped (shielded), and chemically stable.

Equipment on the ground surface at the hole includes:

- Power supply (AC or DC)
- Instrument and probe controls (on/off, open/close caliper, scale setting)
- Winch and depth counter
- Signal receiving and conditioning circuits
- Recorder and/or portable computer
- Well head cable tripod or sheave

Downhole equipment includes the measuring probe, which is connected to the cable by a threaded water-tight coupling. Two or more logging methods can occasionally be performed with the same probe (e.g., SP and normal resistivity). Probes can be changed quickly so that a number of logs can be performed at one borehole with minimal down-time.

Some logging systems are equipped with digital data acquisition systems connected to portable personal computers. Data are sampled at regular intervals (usually six inches or one foot) and stored on magnetic tape or disk. This setup is highly desirable because digital data can be manipulated easily for calculations or presentation. Although tedious, analog data can be digitized at the office using available digitizing hardware and software.

8.3-2.2 Field Procedures

Field procedures for logging generally consist of six steps, as outlined below:

- Equipment setup and assembly
- Verification (or calibration) of probe functions at surface
- Downhole run and total depth determination

- o Main run (uphole as appropriate)
- o Repeat run (if verification of anomalies warrants)
- o After-run calibration

Calibration measures the probe's response to a known standard. Checking the probe response against a known standard before and after a borehole survey ensures that the probe is operating and measuring correctly. After the probe response is calibrated, it is placed at the top of the borehole and the reference point of the probe is positioned at a reference elevation (usually ground surface or top of casing). The depth counter is then set to either zero or ground zero and the probe is lowered to the bottom of the bole. This process is known as depth calibration.

It is customary practice to make a record of log response when lowering most probes to the bottom, although a formal depth-registered log is normally not necessary or practical. However, it is important that the downhole run document the extremes in order to choose the optimal instrument settings for the uphole run, during which a formal depth-registered log is made. (Uphole and downhole recorded logs will not be identical for most geophysical probes because of probe design and delayed response in the direction of probe movement.)

The temperature and fluid resistivity probes are run from top to bottom so that the water in the borehole is not mixed or displaced appreciably by moving the probe. All other geophysical surveys are recorded during probe ascent in the borehole so that constant logging speed and cable tension can be maintained.

Once the probe reaches the bottom of the hole, the optimal instrument settings are activated, and the uphole log is made. The footage dial reading on the winch is recorded on the field chart (analog recorder paper) at the exact point of pen stoppage at the top of the hole to verify depth calibration. Agreement between pen and dial should be within 0.5 foot.

Analog recordings are usually made at a vertical (depth) scale of one inch equals 10 feet; however, a different scale may be used to show more detail, or less detail, if a digital recording is made simultaneously. If the data are not digitally recorded, it is very important to select instrument settings that will result in nearly full chart-width pen fluctuation without reaching the margins of the chart paper. Generally, one set of instrument settings can be selected to achieve this result for the entire depth logged. All setting changes must be accurately documented on the chart (beside the change or in the header), if the log appears uncharacteristic or suspect, the probe calibration is checked. A second complete or partial log should be made if any doubts persist concerning instrument/probe response.

When contaminants are (or may be) present, the cable must be decontaminated as it is removed from the well. When multiple logs are to be run in shallow wells, it is desirable and usually possible to set up the logger at a distance adequate to prevent the wet cable from wrapping on the spool between runs. In this case, cable decontamination is needed only after the last probe is extracted. A preliminary rinse should be performed while the cable is over the borehole. One method for decontamination is to set up stations along the cable for washing and rinsing (for a more thorough discussion of decontamination procedures, see Sections 3.3 and 6.5) as shown in Figure 8.3-1. Another method is to construct a jig to hold sponges and fluids for washing, or properly-attired field personnel can perform decontamination using spray bottles and sponges.

Downhole probes that will be in direct contact with potentially contaminated soil and water must be decontaminated between logging runs. Probes should also be thoroughly decontaminated, taking care to remove all contaminants from moving parts (e.g.. hinges on caliper arms). Without decontamination, contaminants can be transferred onto the spool, contaminating the remainder of the cable or other boreholes.

Borehole methods that employ the use of radioactive sources should only be used in boreholes that are either cased or completed in competent bedrock. Operators of probes with radioactive sources must be certified and licensed by the United States Nuclear Regulatory Commission.

8.3-3 PASSIVE BOREHOLE METHODS (NON-PENETRATING)

8.3-3.1 Borehole Television Camera Surveys

Although the borehole television camera is not technically a geophysical logging method, it is discussed in this section because of its usefulness in the investigation of open hole bedrock wells and the evaluation of casing integrity.

8.3-3.1.1 Principles of Operation

A borehole television camera survey can be made of any well or boring of appropriate diameter that is filled with clear water or air. The camera, similar to a home video camera, is enclosed in a watertight, pressure-safe housing that contains a light source. A coaxial cable is attached to the camera and the light source. The cable allows the transmission of power to the downhole instruments and the transmission of video signal from the camera. Video signals sent up the coaxial cable are viewed on a television monitor at the surface. The survey is also recorded on videotape to permit future analysis.

8.3-3.1.2 Applications

Borehole camera surveys are generally used for inspection of cased borehole sections. Camera surveys can reveal mechanical defects in casing such as:

- Cracks, holes and splits
- Oxidation (rust) of steel casing
- Scaling by contaminants
- Plugging of slots or screen

In an open hole, the borehole camera can assist in determining rock type, layering, the pretence of fracturing, and hole integrity.

8.3-3.1.3 Equipment

A number of borehole camera systems are commercially available. These systems are generally composed of a downhole camera with light source, hand or light duty electric winch with coaxial cable, television monitor, camera control panel, and video tape recorder. Manufacturers' specifications and options, which may vary considerably among systems include:

- o Probe size (11/2-inch to 6-inch diameters are available)
- o Black-and-white or color recording capabilities
- o Size and quality of television monitor
- o Camera lens quality (amount of distortion)
- o Uphole remote controls (amount of light, focus, and aperture setting)
- o Text and depth printed on log (recording)

Borehole cameras need a special coaxial cable for transmission of video data.

8.3-3.1.4 Field Procedures

Camera systems that do not have remote controls for adjustment of focus, amount of light or aperture must be lowered into the bole, checked for picture quality then removed and adjusted if necessary. The camera system should be raised and lowered slowly in the borehole to avoid stirring up sediment that may have settled in slots, the screen, or on the bottom.

8.3-3.1.5 Interpretation

The visual inspection of a borehole or casing requires no special interpretation techniques.

8.3-3.1.6 Advantages and Disadvantages

The borehole camera can provide a very accurate picture of the mechanical condition of the boring and casing. Small features such as open fractures and clogged slots and screens can be observed with this technique.

Resolution of the camera varies considerably between manufacturers. The camera's resolution may not be high enough to show hairline fracturing.

Water clarity is usually a limiting factor in the use of borehole camera surveys. The possible effect of contaminants on the optical lens of the waterproof case should be considered before running a survey. Also, the borehole camera cannot be attached to a standard one- or four-conductor logging cable like those used for electrical, nuclear or caliper logging.

8.3-3.2 Caliper Logging

8.3-3.2.1 Principles of Operation

The caliper tool measures the diameter of the borehole. Spring-loaded arms, hinged to the probe body at their upper end, press against the borehole wall. The hinged end of the arm is connected to a variable resistor. As the arm moves out (in an enlarged section of the borehole), the resistance is lowered and a larger voltage is sent to the recorder and displayed is a change in borehole diameter. Figure 8.3-2 illustrates a three-arm and a four-arm caliper.

8.3-3.2.2 Applications

The caliper log is generally used to assess the variation in hole diameter for use in conjunction with other geophysical logging techniques that are sensitive to borehole size and smoothness e.g., gamma-gamma, neutron, acoustic velocity), when appropriate, caliper log data may be need to determine corrections to other logs. Caliper logs can also be used to find fractures, solution channels, and vugs in hard rock, or to identify depths at which soft formations may be squeezing into the bole and substantially restricting other downhole testing.

8.3-3.2.3 Equipment

The most common and accurate of the caliper probes has three or four arms. Probes with four arms provide two diameters (maximum and minimum). The surface electronics contain opening and closing controls for the probe arms, as well as controls for calibration setting. Both the three and four arm models are calibrated using two different size rings of known diameter.

8.3-3.2.4 Field Procedures

No information can be obtained on the downhole run because the arms will not function properly in this direction. The caliper arms are opened at the bottom and a log is made pulling the probe uphole at a relatively slow rate of 8 to 15 feet per minute, in partially cased boles, the probe should be run in the casing to verify diameter calibration and chock for major casing breaks, if this information is desired.

8.3-3.2.5 Interpretation

The interpretation of the caliper log is straightforward because the hole diameter is recorded directly in inches. Three-arm calipers tend to show the maximum hole size, while four-arm calipers will also show minimum hole size. Fractures, if they are non-vertical, show as sudden increases in borehole size. Fractures less than about 1/4 inch in aperture or those that intersect the borehole at a steep angle may not affect the position of the probe's arms, and go unrecognized.

8.3-3.2.6 Advantages and Disadvantages

The caliper tool gives a good indication of the rugosity (degree of roughness) of the borehole. Data are relatively staple to interpret and should always be run if logging an uncased borehole. The probe requires inspection and possibly cleaning of arm hinges before using to prevent a loss of sensitivity to diameter changes.

8.3-3-3 Temperature Logging

8.3-3.3.1 Principles of Operation

Temperature logging provides a vertical profile of temperature (or differential temperature) in a water-filled borehole. The probe is quite simple and features a thermistor (temperature-dependent resistor) mounted at its bottom end. The voltage across the thermistor is sent to the uphole circuits, voltage readings are converted to counts per second (cps) and cps fluctuation versus depth are recorded directly on the log. Each probe and surface electronics system has a laboratory-derived relationship between cps and temperature in degrees Celsius.

A more sensitive version of the temperature log, called the differential temperature log, is a calculation of the change in temperature between two points in the borehole. Differential temperature probes may contain two thermistors a fixed distance apart, or may contain one thermistor and calculate temperature changes electronically by comparing the present reading to stored data from previous readings.

8.3-3.3.2 Applications

The temperature log is used to help identify the source and movement of water in the borehole. The specific applications include:

- Location of zones of water flow
- Location of leaks in easing
- Identification of discrete aquifers
- Indication of permeability

Temperature logging can also be used to identify the location of cement outside the casing in a grouted hole if the probe is run within 24 hours of cementing.

8.3-3.3.3 Equipment

The equipment needed to run a temperature log includes a thermistor mounted on the end of the probe and protected by a thin metal cage, and a voltage-controlled recorder. The equipment is relatively simple to operate. The typical temperature probe can resolve differences in temperature of 0.02°c, and high-resolution equipment can attain a precision of about 0.001°C.

8.3-3.3.4 Field Procedures

The temperature probe should be the first log run in a borehole if it is to be included in the investigative suite. It should be run from top to bottom to avoid mixing of the water. It is especially important to run the differential temperature probe at a very slow and consistent speed (6 to 8 ft/minute is recommended) so that physical mixing of thermally stratified water will not occur.

Generally, the temperature probe is not field-calibrated. However, its calibration can be crudely checked in air or water if another temperature measuring device is available. The responsiveness of the probe and recorder electronics can be verified by breathing on the thermistor.

8.3-3.3.5 Interpretation

Normally, interpretation of the temperature log is based on the assumption that water in the well is at thermal equilibrium with the surrounding material. Water entering a well bore from different aquifers penetrated by the hole usually will have a different temperature and will cause a flattening or steepening of the log profile. Figure 8.3-3 demonstrates the standard interpretation of various configurations of temperature profiles. An abrupt anomaly on the log is caused by either warmer or cooler water entering or leaving the borehole at the depth of the anomaly. Permeable zones, especially major fractures and casing leaks, can thus be detected as anomalous points on the temperature logs if any groundwater movement is occurring.

8.3-3.3.6 Advantages and Limitations

A temperature log must be made in a fluid-filled hole. The preferred situation for most investigations requires that a borehole has reached thermal equilibrium with the surrounding material and that this equilibrium has not been disturbed by sampling or other downhole activities. Depending on subsurface permeabilities and the degree of thermal disturbance, the equilibration time can vary from a day to perhaps several weeks. In order for this log to reflect natural subsurface conditions, it is also necessary that surficial water does not enter the hole, and that the well construction grout (which gives off heat) has cured for at least three days.

A temperature log is often very informative for holes several hundred or more feet deep, especially where deeper aquifers or fractures exist that are hydraulically not directly connected to a shallow aquifer. The equipment is easy to operate and is relatively inexpensive.

The thermistors may be quite fragile, and downhole breakage can occur if the borehole has edges that may catch the probe.

8.3-3.4 Self Potential (SP)

8.3-3.4.1 Principles of Operation

Electrochemical potentials are generated by interactions between ions in the borehole water and pore water in the borehole wall. The Self Potential (SP) method is a passive technique that measures these naturally occurring voltage potentials in the borehole.

More importantly, in geologic environments in which groundwater enters the borehole through thin permeable zones, voltage potentials can also be generated electrokinetically (creating streaming potentials) when an electrolyte (groundwater) flows through a porous medium (rock or soil).

Zones of water gain or loss are often identified by a streaming potential on the log. Streaming potentials are generally negative and have a spikey, irregular character.

8.3-3.4.2 Applications

SP measurements are used for the following:

- o Identification of zones of water loss or gain (streaming potential)
- o Qualitative indication of clay content/determination of clay layers
- o Qualitative indication of water salinity
- o Rock type correlation/layer thickness

The SP log may be used in conjunction with the resistivity log to identify clay zones. Other logs, such as the neutron, gamma ray or temperature, can be interpreted with the SP to determine lithology and relative permeability. More than any other technique discussed herein, the SP method is not a stand-alone technique; it requires correlation with other logs.

8.3-3.4.3 Equipment

The downhole equipment for SP and resistivity logging includes a probe with lead or copper electrodes connected to the logging cable. The uphole equipment includes the winch, electric control circuits, power supply, and recorder. Correct measurement of SP in a borehole requires that a grounding (reference) electrode or stake, which is electrically connected to the SP measurement system, be driven into the ground at least 25 feet from the borehole.

8.3-3.4.4 Field Procedures

Field procedures for electrical logging follow the same rules as most other logging methods. The probe is lowered to the bottom of the hole and measurements are made as the probe is pulled up the borehole. When making SP and single-point resistance measurements, it is important to have an effective ground electrode. In very hard or dry material it may be necessary to saturate the ground with water or electrolyte so that a good electrical connection exists between the electrode and the surface material.

8-3-3.4.5 Interpretation

The SP log can be interpreted to give qualitative information on clay content and permeability. To accomplish this, a line is drawn on the log at the maximum deflection of the SP as shown in Figure 8.3-4. A second line is drawn along the baseline. Deflections from the baseline indicate permeable zones. The magnitude of the deflection is proportional to the salinity of the water in a clay-free zone and proportional to the clay content in a clayey zone. If the borehole water has a lower ionic concentration than the formation water, the deflection will be negative; however, if the formation water has a lower concentration, the deflection may be positive.

Zones of water loss or gain can be detected as negative excursions from the baseline with a noisy or spikey, irregular character.

8.3-3.4.6 Advantages and Disadvantages

The SP curve commonly has reduced character in holes drilled with natural (formation) water because there is little geochemical activity between the borehole and formation waters. Deflections on the SP log can be very subtle in holes drilled with natural or moderately resistive water so that scales used in presentation must be changed to show greater detail. SP deflections can be reversed in areas where formation water has lower ion concentration than borehole water.

8.3-3.5 Fluid Resistivity

8.3-3.5.1 Principles of Operation

The resistivity of the formation fluid, which is the inverse of the conductance of that fluid, varies as the amount of major dissolved ions of salt compounds vary (i.e., fluids with high NaCl concentrations have high conductance and low electrical resistance). The measurement of fluid resistivity is accomplished by measuring the AC-voltage drop between two closely spaced electrodes on a probe. This technique is the same as that discussed in Section 8.3-4.1 for formation resistivity in which a substantially greater spacing between electrodes causes the electrical field to easily penetrate the borehole environment and focus within the formation. Fluid resistivity is generally recorded in measurement units known as ohm-meters (times a constant that depends upon the manufacturer's design of the logging system).

8.3-3.5.2 Applications

Fluid resistivity logs are used to determine the general water quality with regard to total inorganic compound (namely salts) concentration. This geophysical method is commonly used to detect groundwater-conducting fractures in saturated rock environments. A procedure based on fluid resistivity (conductivity) logging has been demonstrated to quantify inflow rates from fractures into a borehole (Tsang, 1987). Because the SP and other resistivity-type logs are somewhat affected by borehole water quality, the fluid resistivity log can provide information to correctly interpret or quantitatively adjust other logs.

8.3-3.5.3 Equipment

Probes for fluid resistivity logging have two ring electrodes (four if multi-conductor winch-cable systems are used) spaced along a water intake tube that the borehole water flows through as the probe is lowered down the hole. Most groundwater investigative probes will fit into a 2-inch diameter hole, and are designed only for logging downhole. Electrical signals are transmitted to the standard surface electronics module, which converts these to counts per second as is done for most other log types. Some probes will measure both water temperature and fluid resistivity simultaneously. This arrangement is preferred as the water column in the borehole will not have been disturbed for either log type.

8.3-3.5.4 Field Procedures

The operation is very similar to that for temperature logging (i.e., slow downhole log recording). The tip of the probe housing the water intake tube must be kept open and clean. The log is begun with the probe end just under the water level in the well. The most sensitive span setting that will not cause full-scale deflection of the pen should be used, but commonly a conservative setting must be selected in the absence of knowledge of water chemistry variability in a particular logging environment. Dual recording systems (analog and digital) eliminate most problems with log insensitivity.

8.3-3.5.5 Interpretation

The fluid resistivity log is one of the more difficult logs to interpret in the absence of any groundwater quality analysis of borehole water and formation water (if different). The objective of fluid resistivity logging must be reconciled with the known (or unknown) condition of the borehole to derive reliable interpretation of general inorganic water quality. Most important is the status of chemical conditioning of the borehole prior to logging, which usually relates to what fluids were used during the drilling process and what percent of the chemical substances were removed by development of the hole. Conditioning (intentional or unintentional) may greatly influence the degree of difference between in-situ groundwater chemistry and borehole fluid chemistry when the hole was logged.

If logging is to determine natural groundwater quality, the drilling fluid within the borehole and its invaded circumference must be removed or allowed to dilute to the natural concentrations with time prior to logging. In some cases, a return to natural borehole conditions can be knowingly achieved, and in other cases uncertainty will remain.

Interpretation is less complicated when the objective is to correct other resistivity logs, or to identify depths where the formation is actively yielding water to the borehole. In the first instance, the actual resistivity readings with depth are used without environmental interpretation. In the second case, recognition of groundwater inflow (or outflow) from the fluid resistivity log requires identification of trace excursions or offsets that are not the result of extraneous stresses occurring at the borehole. The reliability of fluid resistivity interpretations largely depends on what is known of borehole conditions and on the interpreter's experience.

8.3-3.5.6 Advantages and Limitations

Fluid resistivity logging provides a quick, relatively inexpensive means (as compared to extensive multi-depth water sampling) to qualitatively compare general inorganic water quality in various depth intervals of a borehole. It also may indicate depths where groundwater is moving into an open borehole and serve as collaborative evidence for such movement as suggested by a temperature or flowmeter log.

This technique requires that the hole be uncased, screened, or perforated over the depth interval of interest, and be filled with water to this level. The log must be made going downhole at a slow rate of speed. The most ideal situation for interpretation is that the drilling fluids be thoroughly flushed during development, and that enough subsequent time be allowed for chemical equilibrium to occur.

8.3-3.6 Inhole Flow Measurement (Flowmeters)

8.3-3.6.1 Principles of Operation

Several means of measuring the flow of water within a borehole using wireline geophysical equipment have been developed (Keys and MacCary, 1971, and Patten and Bennett, 1962). Three techniques have been well documented: impeller flowmeter, tracer injection and monitoring and thermal flowmeter. The thermal flowmeter, which measures vertical notion with high sensitivity is a newly tested instrument and, as of this writing (1988), is not widely available. Although it shows much promise for accurately measuring very slow flow rates (Hess, 1982 and 1985), it is not discussed in this section.

Impeller flowmeters measure the revolutions of an impeller or vanes, mounted with its shaft parallel to the probe. This instrument is only capable of measuring flow velocities greater than about one to three feet per minute. Pulses are generated by the interaction between a very sensitive magnetic switch and a magnet placed on a shaft that rotates as a result of current flow. These pulses are sent up-cable to a standard rate-meter module, which registers each pulse on stationary time-drive or continuous depth-integrated logs. The speed of probe movement is critical to the log quality for the latter log type.

The tracer injection technique involves dispersing a "slug" of a tracer, such as salts, trivium, or fluorescein dyes (Driscoll, 1986), at a strategic depth in the borehole, and then monitoring its movement up or down the hole with respect to the exact recording of elapsed time intervals. The tracer hot-spot is assumed to move at exactly the same rate as the borehole water. Detectors located above and below the injection port on the probe are essentially fluid conductivity sensors. These data are used to calculate borehole fluid velocities.

8.3-3.6.2 Applications

Inhole flow logs can be used to determine the rate of water movement between two permeable zones (or fractures) intersected by the open borehole, or opposite well screens or perforations. Rates of movement can be used to calculate a volume flow per unit time, and if the thickness and percent of total flow contribution of the permeable zone(s) are known, hydraulic conductivities can be determined (Schimachal, 1981). As complementary data, caliper logs for open-borehole applications are strongly recommended so as to derive the appropriate representative diameter of the segment through which flow was measured.

Flowmeter logging under conditions of surface discharge of borehole water (pumping or artesian flow) can provide data to interpret percentages of the total flow attributable to each permeable zone. This technique could be applied in competent rock holes to locate a dominant fracture that contaminants might follow and, thus, provide detailed information for discrete chemical sampling.

8.3-3,6,3 Equipment

An impeller flowmeter consists of a vane-type spinner mounted in a vertical axis position inside a strong cage on the bottom end of a probe. The diameter of the probe is smaller than the spinner, which is usually between three and four inches in diameter. The up-hole end of the probe connects to common cable heads. Single-conductor cable flowmeter probes are available. Surface electronics of most standard logging units can receive and process the pulses.

Tracer injector probes are relatively complex, as the tracer solution must be loaded and remotely ejected through small ports on the side of the probe. Because the direction of fluid movement in the borehole is commonly not known beforehand, probes having conductivity (resistivity) detectors both above and below the ejection (ports) should be used because they allow measurement collection while holding the probe motionless in the hole (a very desirable condition). In large diameter boles, the probe should be centralized. To obtain a visual field log, the analog recorder must have a built-in time-drive mechanism, or a computerized digital playback of conductivity readings versus time.

8.3-3.6.4 Field Procedures

Two primary options exist for operating the impeller flowmeter: depth-stationary recording and constant probe-speed recording. The depth-stationary method assumes that borehole water velocity is faster than the stall speed of the meter, either through 1) natural artesian flow out the top of the well, 2) induced flow through pumping of the well, or 3) natural flow between two or more separated permeable zones (a phenomenon known as "thieving"). To collect flow data, the flowmeter is positioned at selected depths, and a time-drive log is made at each for several minutes duration. The log on the right in Figure 8.3-5 shows a typical measurement.

The constant-speed technique is used when the flow in the hole is presumed to be near the impeller sensitivity speed and/or a large depth interval must be logged. Proper procedure requires downhole and upbole log recordings, both made at the identical probe speed. The left logs in Figure 8.3-5 show an example with a probe speed of 40 feet per minute. With speeds of this magnitude, rugosity of open boreholes may cause artificial anomalies if the probe bounces off or momentarily bangs on a protrusion (the operator must carefully watch the cable's action).

The procedure for obtaining tracer injection logs is less rigid; it depends upon the logging system being used, the rate of fluid travel, and if the direction of travel is known beforehand. The user is referred to Keys and MacCary (1971) for consideration of the various options.

8.3-3.6.5 Interpretation

Flow velocity is easily computed from stationary time-drive flowmeter logs by counting the number of pulses per unit time, and applying the calibrated flow rating for each individual probe. Feet per minute of travel is then used to compute the volumetric rate of flow, using the most accurate determination of average borehole (or easing) diameter.

Using the constant probe-speed technique, zones of increased impeller rotation on a log made in one direction and decreased impeller rotation in the opposite log direction are identified as having vertical flow. This phenomenon, as illustrated on the logs shown on the left side of Figure 8.10-5, can be seen to occur between the depth interval of 260 and 270 feet. Again, through calibration of the meter and by knowing the logging speed, the velocity of flow can be computed.

Interpretation of trace injector logs is straightforward, assuming that the tracer plume passes a fluid conductivity detector during the monitoring period. The fluid velocity is computed as the distance traveled between the ejector and the detector (if the probe is held stationary as is normally the case) divided by the time span between ejection and the arrival of the peak conductivity recorded on the time-drive log. If the tracer substance has a specific weight much different than the borehole fluid, density corrections should be made. Radioactive tracers have been very successfully used in combination with gamma detectors installed in an ejector probe because they are detectable at very low concentrations. However, government regulation of radioactive tracers now is very stringent, discouraging their use.

8.3-3.6.6 Advantages and Limitations

Flowmeter logging can provide the best means to quantify natural movement of groundwater between two permeable zones in a borehole. It is the only direct method to determine the percent contribution of various permeable zones when a long section of an uncased bedrock hole, or long screened or perforated casing section, is pumped. Provided that the borehole fluid velocity is greater than 3 to 5 feet per minute, the impeller meter will detect the presence of fractures that are conducting water into or out of the borehole.

Use of flowmeters and other flow detection technologies to investigate groundwater movement is dependent on the existence of natural flow or the use of well pumps to create velocities greater than the detection limits of the technique. Impeller flowmeters must be calibrated in controlled velocity environments, and the meter must be rechecked if any significant wear or damage is suspected and if quantitative results are needed. The technique may not give good results in small diameter (2- to 3-inch) holes. If used in large diameter holes, a skirt should be attached to concentrate the flow past the impeller or sensors. Caliper logging of uncased holes is highly recommended prior to running in-hole flow tests, as not making diameter corrections may cause velocity errors to exceed 40 percent (Schimschal, 1981).

Trace ejector logging may provide reliable results at somewhat lower velocities, but this technique is difficult to use to investigate long sections of borehole. Both methodologies require relatively simple instrument controls and operator training.

Borehole flow logging is more time consuming than most other downhole logging.

8.3-4 FORMATION PENETRATING METHODS

8.3-4.1 Resistivitv Techniques

8.3-4.1.1 Principles of Operation

Resistivity measuring devices (normal, single point and induction/EM probes) measure the electrical resistance of a volume of material around the borehole. These active techniques involve applying a current (AC or DC) to the formation and measuring the resulting potential field. The use of normal and/or single point techniques requires that the borehole be uncased and filled with a conductive fluid. The induction probe, which applies an electromagnetic field to induce currents in the formation, is employed when a current cannot be applied directly, such as in air-filled or PVC-cased holes.

The single-point resistance probe is the most commonly used resistivity device. It consists of a single lead electrode connected to a power source and voltage meter (Figure 8.3-6). A constant current is applied to the electrode and the voltage between the electrode and surface ground, which basically varies with earth resistance, is measured in the same manner resistance is measured with a volt-ohm meter. The actual property measured with the single-point device is resistance, in ohms. Resistivity is a volumetric quantity expressed in ohm-meters.

The normal device, also called the two electrode system, employs the use of two electrodes on a probe, spaced a selected distance apart (see Figure 8.3-6). The lower electrode is used to apply a constant current to the formation. The upper electrode is used to measure the potential field at that point. The electrode spacing determines the depth of investigation of the normal tools. The depth of investigation into the rocks surrounding the borehole is approximately equal to about half the electrode spacing. Common spacings are 16, 32, and 64 inches. Closer spacings may be used to advantage in slotted PVC casing, with minor adjustments.

When borehole conditions (i.e., air or foam filled holes or in holes cased with PVC) prevent a current from being applied directly to the formation, as is the case for normal and single-point methods, an electromagnetic probe, also known as the induction technique, may be used. The induction probe is essentially the same as the surface terrain conductivity instrument described in Section 6. A lower transmitter coil produces an electromagnetic field that generates a ground loop (circular currents around the borehole). The secondary field created by the ground loop in the rocks and fluids surrounding the borehole is measured by the upper coil, and is proportional to the conductivity of the material between the coils.

8.3-4.1.2 Applications

Resistivity logs are used to determine:

- Water saturation
- Porosity (when the conductivity of formation water is known)
- Clay presence
- Basic water quality (i.e.. conductivity due to salts - when the formation porosity is generally known)

Generally, when these parameters are to be determined, a log suite consisting of gamma ray, SP, acoustic velocity (to be explained later in this section) and resistivity is run. Also, the resistivity and induction method can often be used to identify contaminated zones, if the contaminants have an electrical conductivity significantly higher or lower than the hydrogeologic environment and an adequately high concentration is present.

8-3-4.1.3 Equipment

The downhole equipment for single-point resistance and resistivity logging includes a probe with lead or copper electrodes connected to the logging cable. The uphole equipment includes a winch, electronic control circuits, power supply, and recorder. Single-point resistance logging, which utilizes only one probe electrode, requires that a grounding electrode or stake be driven into the ground at least 25 feet from the borehole.

Two induction instrumentations are available for groundwater investigations, with slightly different configurations. A stand-alone portable unit is commercially available which focuses the electromagnetic field into the formation beyond the walls of the borehole. This unit includes a two-coil probe; a 9-mm diameter, seven conductor logging cables; uphole electronics module; power supply (12 VDC); and an analog or digital recorder. The other configuration for the induction logging equipment is a standard multi-conductor probe that is compatible with truck-mounted logging equipment.

8.3-4.1.4 Field Procedures

Field procedures for electrical logging follow the same rules as most logging. The probe is lowered to the bottom of the hole and logs are made as the probe travels up the borehole. When making a single-point resistance log, it is important to have an effective ground electrode. In very hard or dry material it may be necessary to saturate the ground with water or electrolyte so that a good electrical connection exists between the electrode and the surface material. The logging cable must be electrically insulated for a distance of 5 times the electrode spacing when running normal resistivity logs. Logging speeds can be as high as 3 feet per minute for electric logs without losing log quality.

A variable-resistance decade box should be used during each day of field logging to calibrate the system's response output in ohm-meters.

8.3-4.1.5 Interpretation

Resistivity measurements can be used qualitatively to interpret porous water-filled zones or fracture zones. Usually, these zones have lower resistivities than adjacent non-porous or non-fractured zones. After these low resistivity zones are identified, they should be compared to the SP and gamma-ray logs to verify that they are not clay zones which also have low resistivity. The single-point resistance probe is especially sensitive to individual open fractures with apertures greater than about 0.1 foot.

Porosity can be estimated from resistivity logs if the resistivity of the formation water is known. Formulas to calculate formation porosity can be found in Keys and MacCary (1971). For example, formation porosity for sandstone can be determined graphically from Figure 8.3-7.

Qualitative estimates of water quality can be made from resistivity logs in clay-free zones. As specific conductance increases, the resistivity will decrease, assuming the porosity and lithology are constant. Thus, brackish and salt-water aquifers will show lower resistivity than fresh-water aquifers of similar porosity and lithology. Keys and Maccary (1971) and Rwader (1982) describe methods of estimating water quality from electric logs. The methods employ the use of mathematical expressions or cross-plots to relate properties such as formation resistivity factor, fluid resistivity, porosity, cementation factor, specific conductance, and dissolved solids.

When used with the SP and gamma-ray logs, the resistivity log can give valuable information concerning lithology, water content, and groundwater quality. Because electrical current passes through soil by way of water in the pores, it is possible to locate the top of the saturated zone using this method. If a single-point or small-spacing resistivity probe is used, the capillary fringe can often be identified.

Resistivity values are not unique for specific lithologies. However, clays usually have low resistivities and most non-fractured, unweathered igneous and metamorphic rocks have high resistivities. Fresh-water saturated sands normally have resistivities significantly greater than clays. Fine-grained sands and silts commonly have lower resistivities than coarser sands and gravels. In coastal environments, the resistivity log is used to discriminate the higher resistivity fresh-water aquifer from the lower resistivity brackish or saline sea-water aquifer.

8-3-4.1.6 Advantages and Disadvantages

Borehole electrical methods are rapid, repeatable and well documented techniques that require simple equipment and all can be run in two-inch ID holes. They are effective methods for determining the presence of clay layers and water quality.

The primary disadvantage of the electrical methods is that (with the exception of induction/electromagnetic techniques) they require water-filled uncased boreholes.

Another disadvantage is that these methods generally require a fracture with an aperture greater than 0.1 foot.

The induction/electromagnetic probe is effective in low to moderate resistivity formations, and provides resistivity data under conditions where other techniques cannot be applied (air-filled boles and PVC-cased holes). A disadvantage of the induction/electromagnetic technique is that it has poor vertical resolution (cannot resolve layers less than 2-3 ft thick) and gives unreliable data in high resistivity formations.

Resistivity and SP measurements are very sensitive to the resistivity of the drilling fluid. If drilling fluid is highly resistive and the borehole diameter relatively large, thin beds and more resistive beds will not be detected, as most of the current is forced to travel along the borehole walls (Kwader, 1982).

In glacial terrain, boreholes must be cased with PVC or steel. Use of these materials usually precludes single-point, normal resistivity and SP methods, although they can be run in the screened interval of PVC-cased wells. Care should be taken to ensure the integrity of the borehole so that expensive logging probes are not lost by collapsing sections of the borehole.

Electrical methods provide calibrated, quantified results in low to moderate resistivity, water-saturated rocks and soil, such as clays and saturated sand and gravel. Electrical methods give only qualitative to semi-quantitative results in high resistivity materials, such as unfractured granite or dense silty till.

8.3-4-2 Acoustic (Sonic) Methods

8.3-4.2.1 Principles of Operation

Acoustic borehole methods are a group of active techniques that use sound waves to measure the acoustic properties of the soil, rock, and fluid near the borehole. The velocity with which sound propagates through the materials, and/or the strength of the signal at the receiver, are evaluated in conjunction with other geophysical techniques (i.e., SP, Resistivity) to determine the type of the material penetrated. The techniques include:

- Velocity logging
- Amplitude logging
- Wave-form analysis
- Acoustic televiewer

The most common of these techniques is velocity logging. The acoustic methods can be used in open or cased holes. A fluid-filled hole is usually required to transmit the sound wave to the formation. Dry hole acoustic probes are available, but have limited applications. A discussion of basic acoustic logging methods can be found in Labo (1987) or Key and MacCary (1971). More detailed information on the acoustic televiewer can be found in Paillet (1980) and Zemanek and others (1968).

In its simplest form, the acoustic velocity logging technique uses a sound-wave source generator and a receiver mounted on a probe at a fixed distance from the generator (Figure 8.3-8). The generated sound wave is propagated through the borehole fluid and refracted into the formation. A portion of this acoustic energy travels parallel to the borehole and is refracted back to the receiver. Electrical circuits are used to measure the transit time for the sound waves to travel from source to receiver. These data are presented on the log as travel time, recorded in microseconds per foot. Many acoustic velocity logging systems are designed with two or more receivers and two sound-wave generators to minimize the following borehole effects:

- Travel time through borehole fluid
- Irregularities in borehole size (indicated by caliper logs run in uncased holes)
- Orientation of the probe in the hole

Multiple-receiver probes (see Figure 8.3-8) measure travel time by taking the difference between the first arrival of the sound wave from the near and far receivers. Some logging systems are also equipped to record the strength, or amplitude, of the first arrival, usually in millivolts. These acoustic logging systems contain an oscilloscope which allow the entire wave train to be observed while logging. The wave train can also be photographed or recorded digitally so that a complete analysis of all portions of the wave may be performed.

The acoustic televiewer is an elaborate probe that contains one or more sound-wave source generators and receivers mounted radially on an internal rotating mechanism (Figure 8.3-9). The rotating mechanism is powered by a small electric motor and contains a magnetic orientation device used to tie the acoustic measurements to compass directions. As it rotates, high frequency sound waves are generated and reflected off the borehole and back to the probe. Receivers, located coincident with the sound-wave generators, measure the amplitude of the reflected wave and send the information uphole. The wave amplitude data is combined with the simultaneously collected probe orientation and depth information to produce an uncoiled 360-degree acoustic image of the borehole (Figure 8.3-10).

8.3-4.2.2 Applications

Acoustic velocity measurements can be used to determine

- o Porosity (for known lithology)
- o Lithology (determined in conjunction with other logs)
- o Rock strength
- o Fracture location
- o Validity of seismic refraction interpretations

Porosity can be determined from the acoustic velocity log if the formation compensation is known and is clay-free, consolidated (grains cemented together) and fluid-bearing. The porosity is calculated from the relationship established by Wyllie (1963), which involves transit times through the rock and the pore fluids.

The accuracy of the calculated porosity is dependent on the accuracy of the matrix identification. Because the acoustic travel time varies with porosity and rock composition it is a non-unique response. Lithology can only be confirmed if other logs such as the neutron, gamma-gamma or natural gamma are used for verification. The acoustic travel-time log can be used to verify seismic model layers determined by the seismic refraction method (Section 3).

Matrix travel times for sedimentary rocks (shale, sandstone and limestone) are well documented and vary within known limits. Matrix travel times for igneous and metamorphic rocks vary considerably and are not well defined by the present literature. For this reason it is recommended that the interpretation of the acoustic velocity log be limited to identification of relative changes in porosity in igneous and metamorphic rocks, unless detailed information concerning rock type or seismic velocities are available. Dobrin (1976) provides a table of velocities for various sedimentary, igneous and metamorphic rocks (Table 8.3-2).

Relative rock strength can be estimated from acoustic travel-time data in zones of similar rock type. Increases in travel-time can indicate zones of weathering, alteration or fractures, which also have higher porosity than rock outside such zones.

The acoustic amplitude log can be used as an indication of conditions at the edge of the borehole, such as cement bonding quality between steel casing and the formation. If there is a good bond, the acoustic amplitude is high. However, if there is a gap caused by partial grouting, the signal from the formation will be weak (attenuated) and show as a low-amplitude zone. Low amplitude can also be an indication of fractures, unconsolidated or soft material, weathering, or mineral alteration in uncased holes.

The full waveform acoustic log records the complete acoustic wave so that various components of the wave may be identified. These components include the arrival times and amplitudes of:

- o Compressional waves
- o Shear waves
- o Tube waves

Shear- and tube-wave data can be used to locate fractures and estimate permeability. The shear-wave and tube-wave information also is used to calculate engineering properties used in the design of remedial structures or systems. These engineering properties are:

- o Bulk modulus
- o Shear modulus
- o Poisson's ratio
- o Young's modulus

The reader is referred to Dobrin (1976) for a complete discussion of the calculation of these properties from seismic and acoustic log data.

The acoustic televiewer is used primarily to identify and measure the strike and dip of fractures. However, it can also be used to identify other borehole and rock conditions such as hole enlargements, hole obstructions, rock breakouts, foliation, and zones of weakness due to weathering or alteration.

8-3-4.2.3 Equipment

Acoustic logging methods require relatively complex electronic systems and instrument controls to produce acoustic logs. Sophisticated timing and measuring circuits are used to pulse the sound-wave generators and turn the receivers on and off. An oscilloscope is used to visually inspect the quality of the sound wave as it is transmitted and received. All of these components are contained in the surface electronics package. The probe contains the sound-wave generators and receivers. A specially designed camera may be necessary to record the full waveform acoustic log.

8.3-4.2.4 Field Procedures

The acoustic televiewer logs must be run at very slow probe speeds, commonly four feet per minute. Calibration of acoustic surface electronics is generally performed internally by passing a reference signal through the circuits. There are no calibrations needed for acoustic probe electronics apart from the surface system calibration. For quantitative velocity determination, it is best to calibrate the system by correlation with velocities determined by core tests or a seismic refraction survey.

8.3-4.2.5 Interpretation

The porosity value calculated from the acoustic velocity log represents the primary (intergranular) porosity only. Secondary porosity created by vugs, dissolution, and fractures is not detected by the acoustic velocity method because the sound wave travels along the fastest path, which is through the rock rather than the fluid. If the total porosity from the density or neutron log is compared to the primary porosity from the acoustic velocity log, the amount of porosty due to vugs and fractures can be determined.

When the amplitude of the received sound wave is low due to inhomogeneities in the rock (fractures, vugs), the first arrival of the sound wave may not be detected because it is below the detection limit of the probe. Later arrivals with higher amplitudes trigger the detector and show as very long travel time on the log. This phenomenon is called "cycle skipping." The log usually looks very spikey and irregular when cycle skipping occurs. Cycle skipping may indicate vugs, fractures or weak rock.

Acoustic travel times for specific depths can be plotted against gamma-gamma, neutron, or natural gamma count rates at corresponding depths to define rock-type groups (Figure 8.3-11). This technique, called cross-plotting, is very informative, especially when combined with core or other geologic data.

Full acoustic waveform interpretation is similar to vertical seismic profiling (VSP) interpretation; therefore the reader is referred to Section 8.3-4.4 for a more complete discussion.

Interpretation of acoustic televiewer images (logs) is somewhat subjective unless borehole wall character is evidenced on other logs. The basic premise is that strong signals from smooth borehole walls of competent rock appear as bright areas on the log, whereas fractures, soft seams and weathered rock appear as dark areas.

8.3-4.2.6 Advantages and Disadvantages

The acoustic probes are advantageous because they provide perhaps the most accurate information concerning fracture location, geometry and characterization, and need not require confirmation by other log types for some purposes.

The primary disadvantage of acoustic velocity techniques is their relatively high cost and complexity, and their limited value in cased holes penetrating unconsolidated materials. The acoustic tools must be run in water-filled holes so that the sound wave is effectively transmitted to the borehole walls. However, special receivers are available for use in dry holes, but they must be clamped to the side of the borehole, thus preventing continuous logging of the hole.

The acoustic televiewer is not readily available among geophysical contractors, because it is an expensive, relatively specialized probe. Furthermore, the quality of the log, and thus reliability of interpretation, depends strongly on the operator's experience and ability to set the proper acoustic focus. As major changes in the borehole diameter occur, refocusing is commonly required.

The reader is referred to Zemanec and others (1969 and 1970) or Taylor (1983) for a complete discussion of the interpretation of the technique.

8.3-4.3 Nuclear (Radiation) Methods

8-3-4.3.1 Principles of Operation

Nuclear logging methods include both passive (natural gamma-ray) and active (gamma-gamma and neutron) techniques. These techniques are used primarily for the determination of porosity and lithology. Most nuclear methods employ the use of geiger tubes or scintillation crystals to detect the intensity of radioactivity. The detector emits photons (flashes of light) when struck by radioactive particles (neutrons and gamma-rays). The photons are converted to electrical pulses and sent uphole to counting and timing circuits, where a surface electronics module converts these pulses into counts per second. All nuclear logs can be run in open or cased holes, and in dry or water-filled holes.

8.3-4.3.1.1 Natural Gamma-ray Log

The natural gamma-ray log is a measure of the naturally occurring gamma radiation in the formation. Natural gamma radiation is produced by the radioactive decay of potassium, thorium (Th) and uranium (U) atoms. Clay minerals show high gamma ray readings because they commonly contain potassium in their chemical structure. Clay minerals also promote the adsorption of positive ions, such as Th+ and U+, because of their open crystal lattice structure and net negative charges. Thus, the natural gamma log serves as a reliable clay indicator in those environments where non-clay beds do not contain radioactive minerals. However, some granites and their weathering products are also rich in radioactive minerals, and also will give high gamma-ray counts.

8.3-4.3.1.2 Gamma-gamma Log

Gamma-gamma logging uses a solid, encapsulated radioactive source (generally cesium-137 or cobalt-60) mounted 10 to 35 inches from the detector to bombard the formation with medium-energy gamma-rays. The gamma-rays are scattered as they collide with the electrons of the material in the formation. With each collision, an individual gamma particle will lose some of its energy until it reaches a low energy state and is absorbed by an electron. The probe measures the number of gamma rays that are reflected back to the detector. The number of electrons detected by the instrument is inversely proportional to the density of the formation evaluated. Therefore, very dense formations, which have high electron densities and will reduce gamma energy quickly, will cause fewer gamma rays to reach the detector, while less dense formations will exhibit higher gamma count rates. If the formation lithology (and density) are known, variations of density measured can be attributed to changes in porosity.

8.3-4.3.1.3 Neutron-epithermal-neutron Log

The neutron-epithermal-neutron log is used to determine porosity as a function of formation hydrogen content. The basic assumption in the calculation of porosity using this method is that all pore (void) spaces in a formation are water filled. This survey method can be employed below the water table to measure porosity and above the water table to indicate relative moisture content in the unsaturated zone.

The neutron probe is similar in design to the gamma-gamma probe, except an americium-241 beryllium radioactive source is installed. This source emits fast neutrons, which collide with atoms in the formation and are slowed down. The most effective atom in slowing down fast neutrons (because of its similar atomic mass) is the hydrogen atom, which is a major constituent of water. When neutrons reach a very low energy level, they are captured primarily by hydrogen atoms, and gamma energy is released. Detectors are designed to detect (count) either neutrons or gamma photons released by neutron collisions. The counting rate for both types of detectors is inversely proportional to the hydrogen content of the formation. The instrument detection results are converted to porosity.

Although a neutron log cannot be used for measuring porosity above the water table, it is very useful for measuring changes in the moisture content.

8.3-4.3.2 Applications

Nuclear techniques are used primarily to identify the presence of clay, correlate lithologies, and determine porosity. These techniques are most valuable if the probes are calibrated with appropriately constructed field standards of known properties, and, therefore, accurate densities and porosities can be determined. The gamma-gamma and neutron radiation logs provide a record of count rate, which must be scaled with a calibration rating curve after dead-time corrections are applied (moderate to high count rates only) to provide porosity values.

Natural gamma and neutron logs can aid in the identification of perched aquifers, especially when used with a resistivity technique. Opposite a perched aquifer the resistivity is low; the neutron log would show increased water content, and the natural gamma should confirm the perched zone to be non-clayey materials. As the resistivity and neutron probe responses may be similar for clay and water-saturated sands due to water molecules bound to the structure of clay minerals, the natural gamma log is critical for correct interpretation.

8.3-4.3.3 Equipment

The three nuclear techniques use very similar surface and downhole equipment. While a few nuclear logging systems use the same probe and detector for all three methods, with only the source and source-to-detector spacings changed, most logging systems employ the same probe for natural gamma and gamma-gamma, but a different probe for neutron. The uphole electronics consists of a counting and timing circuit for recording data in counts per second. A more complex electronics package is required for directly recording porosity during gamma-gamma or neutron logging.

The gamma-gamma and neutron methods require the use of a solid, encapsulated, chemical radioactive source. Although these sources are relatively small, they present a safety concern for the operators of the equipment. The sources are regulated by the Nuclear Regulatory Commission (NRC) and must be licensed. Use of licensed sources is limited to those persons who have proper training and have obtained NRC certification in nuclear materials handling and safety. These sources are transported and stored in locked, shielded carrying cases and are secured to the probe only during actual logging.

Another aspect of safety is the use of active sources in uncased, loose formations. The potential for getting a probe stuck in the hole often is significant when borehole walls consisting of unconsolidated soils are unstable. It is recommended that no probe with a radioactive source be run in an uncased hole in an unconsolidated formation.

8-3-4.3.4 Field Procedures.

Nuclear logging methods follow the same general field procedures as other logs. One notable difference is that radioactive sources used with the density and neutron techniques are installed using a site-specific field routine that minimizes radiation doses to the operator. Also, log quality and repeatability are enhanced if a probe decentralizer is used in hole diameters of 8 inches or greater. Probes are calibrated at the site using either a source of known strength (field standard) to check detector response or a piece of material with known physical properties to check total probe response.

For uncased holes in competent rock, a caliper probe is always run before the nuclear probes because of the serious consequences of getting a radioactive source stuck in the hole.

Radiation probes are generally run at a slower speed (10-15 ft/min) than most other probes so that the count rates can be averaged over a longer period of time, thus reducing the statistical variability and making the logs more repeatable.

8.3-4.3.5 Interpretation

None of the radiation logs have a unique count rate response to individual lithologies (see Figure 8.3-12); however, within a single geohydrologic environment, any given geohydrologic unit (layer) generally shows a consistent response. This aspect gives these logs much value in correlating lithology between well sites.

Natural gamma logs respond primarily to the amount of potassium, and secondarily to the amount of thorium and uranium isotopes in the formation. As potassium is a major component of most clay minerals, the natural gamma log is generally considered to be a clay-content log.

Other minerals that can cause high gamma counts include:

- Feldspars (high potassium) - found in many granites and other light-colored igneous and metamorphic rocks
- Micas (high potassium; may contain thorium) - found in granites
- Hornblende (can contain thorium and uranium) - a common accessory mineral in granites and some metamorphic rocks
- Uranium minerals in granites and sands

Sometimes, a natural gamma log will show high radioactivity opposite fractures or fractured zones in bedrock. These spikes are usually due to uranium-rich mineral precipitates lining the fracture walls, but small excursions on the log may represent clay-filled fractures.

Natural gamma log responses should be cross-examined with the SP and one of the resistivity log types to confirm rock type. Fractures can usually be identified with the single-point resistance log.

Neutron logs will respond to water bound in the crystal structure as if it were pore water. It is important to check for the presence of clay with SP or natural gamma when using the neutron log to determine porosity. The neutron probe is affected by borehole enlargements and high chloride content. Under these conditions, the neutron log should be used only as a general indicator of porous zones.

Rocks and glacial sediments show an extremely wide range of bulk densities (the combined density of rock, fluid, and air). If the lithology is known, a reasonable estimate of porosity can be made by using published relationships.

The density log can also be used to detect voids and channeling in grout behind casing. Voids and channels in grout may provide pathways for transport of water and contaminants between layers.

When analyzed together, the gamma-gamma and neutron logs commonly indicate zones of formation washout that exist behind the well casing, caused by the drilling process. Washouts and aquifers may give a similar response on these logs, and commonly the natural gamma log must be consulted.

8.3-4.3.6 Advantages and Disadvantages

Nuclear techniques work well in a wide variety of borehole environment including cased (PVC or steel) and uncased holes in saturated and unsaturated formations. Their primary advantage is that, when properly calibrated, these logs give estimates of porosity and lithology that are consistent with independent field and laboratory test results. The porosity and lithology measurements are made in-situ at accurately known depths, thus reducing cost and time involved in comparison to core sampling and aquifer test pumping.

Most of the probe response in nuclear logging is from the first six inches to one foot of the formation surrounding the borehole. Sometimes this zone may be very disturbed, due to drilling and completion procedures that may force drilling fluids into pore spaces near the borehole or alter the compaction of loose materials. If large augers are used and a small diameter well is installed, most of the radiation response is from the gravel pack (filter sand) or backfilled material. In such cases a false indication of formation properties may be obtained. The best hole conditions result from driving casing or open-hole drilling in competent rock.

Hole diameter variation and rugosity of the borehole walls affect all nuclear logs to some degree, depending on source strength and the chosen spacing between source and detector. Gamma-gamma density logs made with a weak radiation source and short spacing may be severely affected, misrepresenting true formation density. Neutron probes have a lesser sensitivity to the same conditions, while natural gamma logs generally are not significantly affected unless a large void or washout is present. Caliper logging in open holes provides data for correcting radiation logs for hole diameter variations. However, quantitative determination of density and porosity opposite washouts in cased wells is not possible.

Radioactive sources are regulated by the NRC and must be licensed. The use of geophysics tools employing radioactive sources is restricted to only those persons who have NRC certification. The consequences of losing a radioactive-source (i.e., by being unable to retrieve a downhole source/probe) is serious and costly.

8.3-4.4 Vertical Seismic Profiling (VSP)

8.3-4.4.1 Principles of Operation

Vertical Seismic Profiling (VSP) is a borehole seismic survey method used to detect and characterize open fractures within rock. The VSP method was developed in the petroleum industry and has recently been applied to hydrogeologic characterization for environmental studies. This method provides a three-dimensional image of subsurface velocities and geologic structure, utilizing an array of seismic borehole geophones (motion sensitive sensors) or hydrophones (pressure sensitive sensors) placed in a borehole at the depths of interest. The technique is illustrated schematically in Figure 8.3-13.

The VSP technique uses a seismic source, placed at the surface some distance away from the borehole to generate seismic waves, which travel through the ground and are detected by the geopbones in the borehole. These waves consist of compressional waves (P waves) and shear waves (S waves). Figure 8.3-13 shows a schematic representation of the seismic wave received by the geophones.

When a fluid-filled fracture, which intersects the borehole, is squeezed by compression from a seismic wave, a pressure pulse known as a tube wave is generated in the borehole. The tube wave is detected by the geophones as the pressure pulse is propagated upward and downward in the borehole. The size (amplitude) of tube waves generated by a permeable fracture depends on the hydraulic conductivity of the fracture, elastic properties of the rock, fluid properties, and borehole radius. High permeability fractures yield large amplitude tube waves. Tube wave amplitudes are generally much larger than those of compressional waves (see Figure 8.3-13).

8.3-4.4.2 Applications

A particular application of this technique is the detection of open, water-filled fractures that are intersected by a borehole (Levine and others, 1985). Compressional, shear, and tube waves can be used to characterize the fractures in terms of depth, attitude, and hydraulic conductivity.

When the formation and fluid properties are known, tube wave amplitudes can be used to determine the hydraulic conductivity (K) of a fracture. The K value is determined through the comparison of compressional wave pressure amplitude to that of the tube wave as measured by the hydrophone positioned closest to the fracture depth. The use of the nearest hydrophone removes the effects of the source as well as the recording system response.

If desired, the lateral extent of the fracture can be delineated by moving the surface source away from the borehole and observing changes in the transmitted and reflected compressional and shear waves (see Figure 8.3-14). Because the compressional and shear waves scatter, attenuate, reflect, and refract at a fracture zone, computer ray-tracing methods can be used to image the geometry of the fracture. Of particular note is the significant attenuation of shear wave energy through a fracture zone or other low velocity zone.

8.3-4.4.3 Equipment

A string of hydrophones or undamped geopbones are used in the borehole to detect the tube waves. The hydrophone responses are transmitted to a surface recording unit. This surface unit should consist of digital recording instrumentation capable of timing in the range of tens of microseconds and with playback capability for later analyses.

The VSP technique generally uses conventional seismic sources (e.g., weight drop, explosives, Betsy seisgun) placed on the ground surface at appropriate locations or within nearby shallow borings. The energy source with the highest frequency content consistent with the attenuation characteristics of the earth materials at that location should be used.

8.3-4.4.4 Field Procedures

The following field procedures allow fracture characteristics, primarily depth, length, and orientation, to be determined.

Surface energy sources are arranged in a radial pattern around the bole and placed at various distances from the borehole. Receivers are placed within the uncased bedrock segment of the borehole. Each source location is detonated individually, with data being stored digitally for each geophone for each shot. After all seismic recordings are made, the sensor array may be raised or lowered in the borehole to span deeper or shallower unmonitored segments. Sensor spacings are directly related to the degree of accuracy with which individual fractures or fracture zones need to be defined. Wide sensor spacings (25 to 50 feet) are useful in identifying depths to zones of fractures; closer sensor spacings (5 to 10 feet) may identify individual fractures. Additional data are recorded until the entire water-filled section of the borehole has been surveyed.

The data are stored on magnetic tape or disk for further computer processing, such as amplitude, frequency and particle motion analysis. A complete display of VSP data from the top to the bottom of a borehole can also be made using the stored data.

8.3-4.4.5 Interpretation

Tube waves indicative of permeable fracture zones are often readily apparent on the seismic recordings. By using an appropriate X-Y data display (individual sensor seismograms with time along one axis and depth along the other axis), the depth at which the tube waves originate can be determined within a few feet if closely spaced sensors are employed. The orientation of the fracture can be approximated by analysis of the tube-wave to compressional-wave amplitude ratio. Geophone records from energy sources located at the same distance, but different angles, around the borehole are used for this analysis. Because of the qualitative nature of the analysis, results are presented in terns of shallow-, moderately-, or steeply dipping fractures. Analysis of the amplitude ratios will define the strike of steeply dipping fractures to within ±10 degrees, and that of moderately dipping fractures to within ±15 to 20 degrees. The more data available from different azimuths, the better is the fracture orientation definition.

The continuity and extent of fractures can best be determined if multiple boreholes are investigated. If a fracture intersects two boreholes, the continuity of the fracture can be determined through computer modeling and imaging. Borehole-to-borehole seismic methods can also be used to establish fracture continuity through the use of guided wave technology (i.e., energy generated in the vicinity of permeable fractures in one borehole and high-amplitude, high-frequency seismic waves recorded in an adjacent borehole).

The tube-wave amplitude is generally influenced by the hydraulic conductivity of the fracture. Other factors such as the physical properties of the medium surrounding the borehole, the frequency of the seismic waves, the properties of the fluid filling the borehole, and the radius of the borehole may also affect the amplitude. The amplitude ratio (tube-wave to P-wave) versus frequency is the key relationship used to establish the hydraulic conductivity of a fracture zone. A set of curves can be generated showing amplitude ratio versus frequency for different hydraulic conductivity values. A set of such curves is shown on Figure 8.3-15. The determination of hydraulic conductivity values by the VSP technique has been verified through correlation with permeability test data.

8.3-4.4-6 Advantages and Disadvantages

Vertical seismic profiling yields clear and definitive results for identifying permeable fractures intersecting a borehole. As numerous studies have shown, some fractures detected by other logging techniques, such as acoustic logging, borehole televiewer, electrical and caliper logging, are not permeable and are not fluid conductive.

The VSP technique has been used in all types of rock with varying degrees of success. The greatest successes for fracture and hydraulic conductivity objectives have been achieved in igneous and competent metamorphic rocks, which appear to have rather distinctive faulting and fracturing zones. Its use in sedimentary rocks and weathered metamorphic rocks, which may have extensive zones of permeable materials, has been less successful.

VSP results away from the borehole are limited to the seismic-ray paths from the seismic source to the detectors. This procedure may, or may not, be sufficient to determine the lateral extent of a fracture away from the borehole and provide control on the attitude of any permeable fractures identified.

The VSP technique requires relatively sophisticated equipment when compared with many of the other borehole techniques. It is also time-consuming and, thus, relatively expensive.

8.3-5 GLOSSARY

Active technique - A technique in which a stress is applied to the material under study and the resultant response is measured. Stresses can include electrical current, sound waves, or neutron or gamma ray bombardment.

Calibration - The process wherein the zero and sensitivity of the logging circuitry is set so that the recorded measurements will be accurate with reaped to industry-standard units of measurement for a specific log-type (i.e., grams/cubic centimeter for rock density).

Dead time - In radioactive logging, the length of time (usually measured in microseconds) required by a logging system to recover from counting one disintegration event in order to count (record) the next event. Events occurring during dead time are not counted.

Formal depth-registered log - A geophysical log recorded on graph paper or digitally in which accurate downhole depths are simultaneously and systematically registered opposite corresponding log responses, and detailed logging run information is recorded in a log header.

Lithology - The physical character and composition of a rock, implying a specific rock or soil type.

Measuring point - The point, on a probe, where the reading is taken (e.g., the tips of the caliper arms; the detector on a gamma-ray probe).

Non-unique response - Response that is not unique to a specific rock characteristic. As examples, several different rock types exhibit low gamma-ray counts; or water-filled fractures and clay layers both have low resistivity values.

Passive techniques - A technique that measures properties inherent to the material. Examples include SP, gamma-ray, temperature.

Probe - The downhole electronics and detecting/measuring apparatus of the logging system, usually encased in a stainless steel jacket.

Radioactive decay - The transformation of an unstable isotope into an isotope of another element, resulting in a loss of energy and the emission of radiation (e.g., alpha or beta particles, neutrons and/or gamma rays).

Reference elevation - The aboveground elevation, which is designated as a common point for referencing all measurements for correlative purposes (commonly, ground surface or top of casing).

Resolution (vertical) - The capability of a logging system to distinguish geophysical changes between closely spaced (thin) lithologic units.

Rugosity - The degree of roughness or irregularity of the borehole wall, which affects some log types.

Total depth (TD) - The deepest point in the boring as determined by accurate measurement, in this instance geophysical logs. Discrepancies commonly occur between total drilling depth and total depth from geophysical logs, due to filling of the bottom of the borehole from caved material or to cable stretch (very deep holes only).

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SECTION 8.3
BOREHOLE GEOPHYSICS
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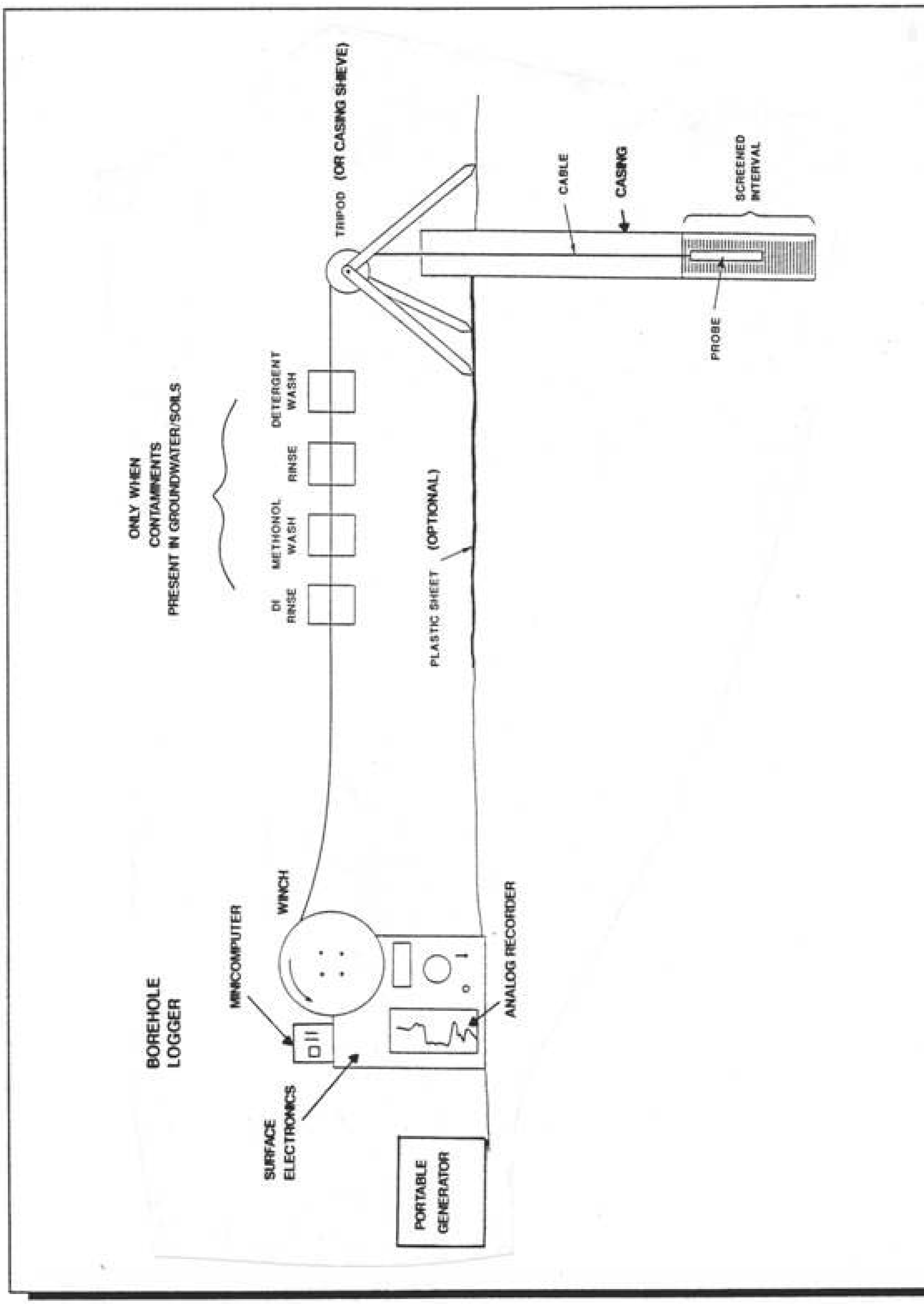


Figure 8.3-1
Typical Geophysical Logging Setup

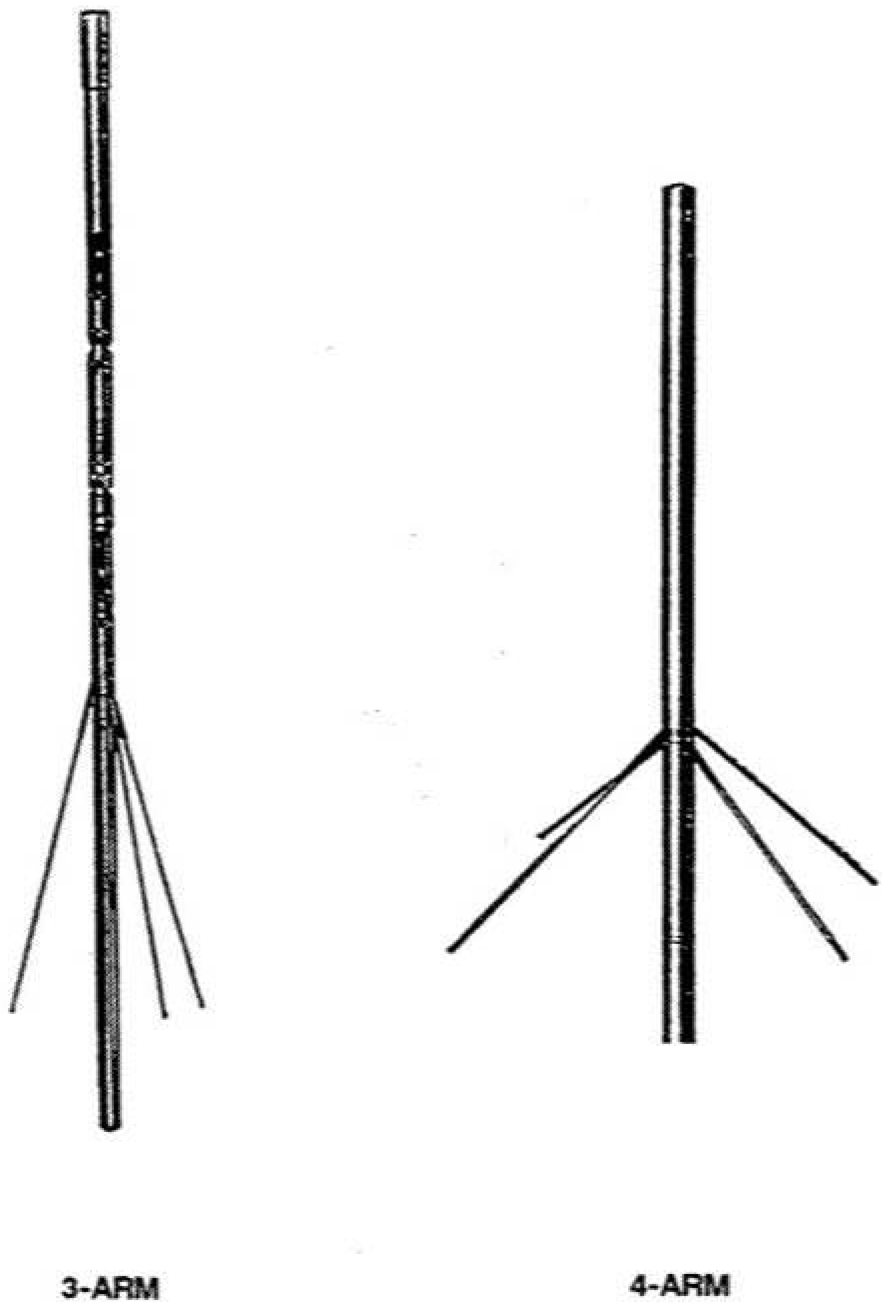
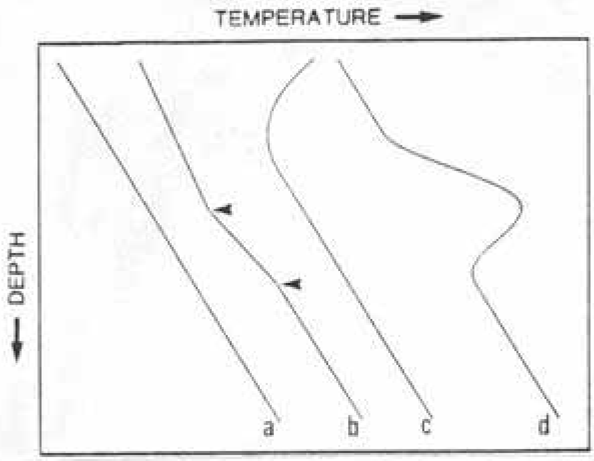


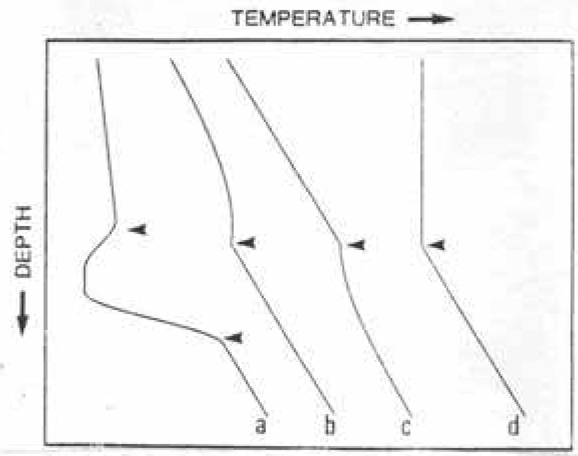
Figure 8.3-2

Caliper Probes



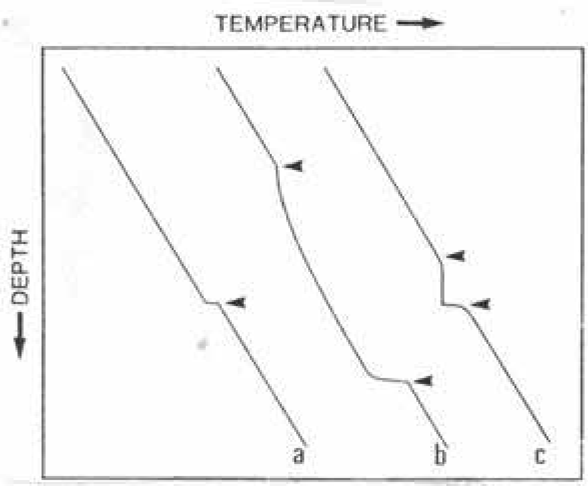
Geologic Controls

Figure A - *Curve a* shows a temperature survey in a thermally stable borehole through a uniform, homogeneous formation. There are no disturbances of any kind. *Curve b* shows a log through three different parallel, homogeneous formations having three different thermal resistivities. The bed boundaries are indicated by the two arrows. *Curve c* shows what the effect of a warming trend on the surface of the ground might be. *Curve d* shows the effect of the exothermic reaction involved in fresh cement setting behind the casing.



Groundwater Controls

Figure B - *Curve a* shows how a permeable zone can appear on a temperature log in a borehole after a period of circulation of liquid colder than the rock in that region. The permeable zone is bracketed by the two arrows. The thermal gradient in the upper portion of the borehole has be changed a great deal by the circulating liquid, and the permeable zone where circulation was lost stands out as an anomalous low-temperature region. *Curve b* shows the effect of liquid entering the borehole at the arrow and flowing upward. The effect of the liquid flowing in the borehole can be manifested in the temperature log in many ways depending on flow rate, flow direction, properties of the rock, and number and nature of the zones of entry and exit of the liquid. *Curve c* shows the effect of liquid entering the borehole at the arrow and flowing downward. *Curve d* shows the same condition as Curve b, but with the liquid flowing much faster.



Special Conditions

Figure C - *Curve a* shows liquid entering the borehole at the bottom and flowing upward, exiting at the arrow. *Curve b* shows liquid entering the borhole at the upper arrow and flowing downward to exit at the lower arrow. *Curve c* shows what might happen if the tool hangs up on the way down the hole, and then drops free after a short period of time.

From: Conaway (1987)

Figure 8.3-3

Interpretations of Borehole Temperature Profiles

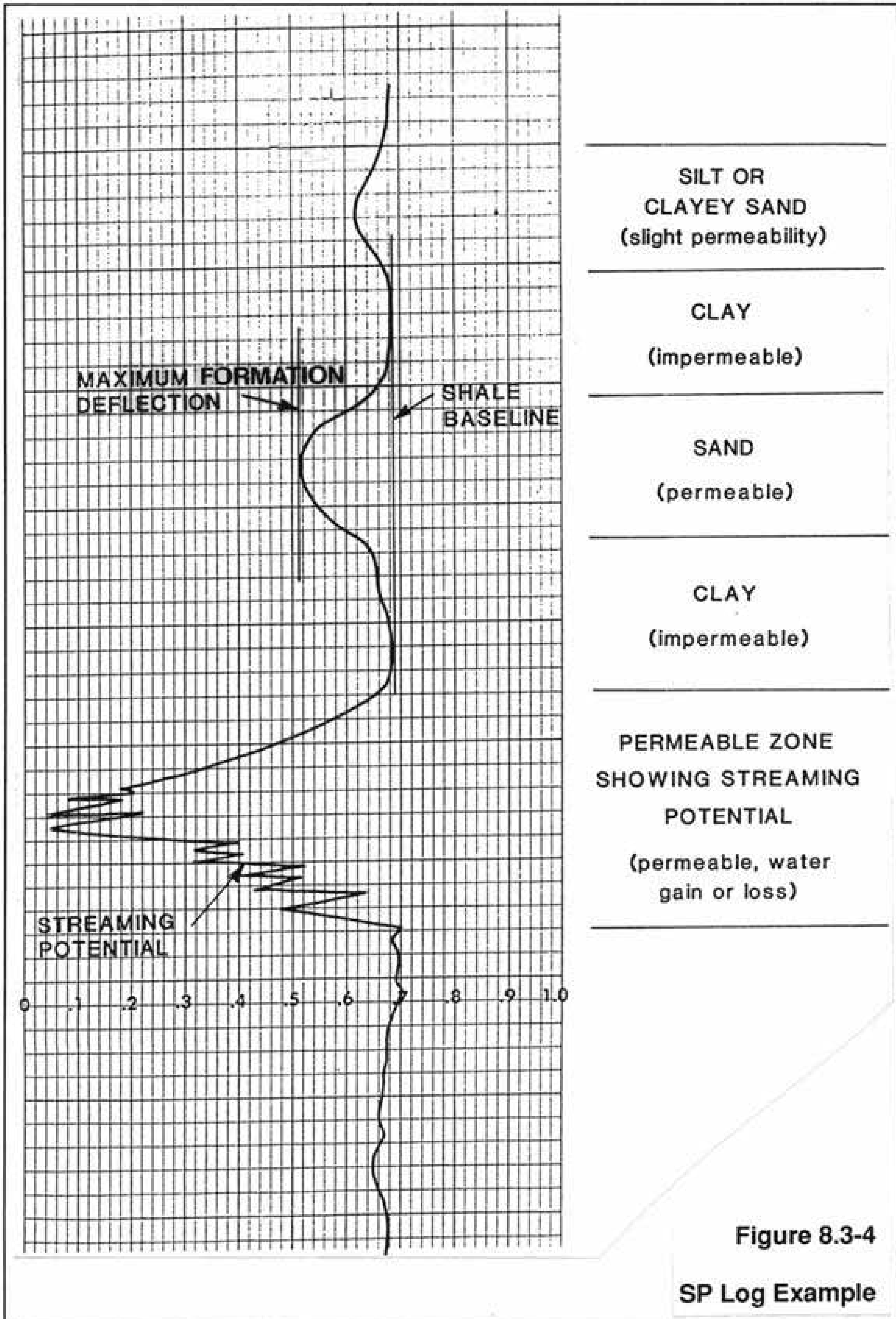
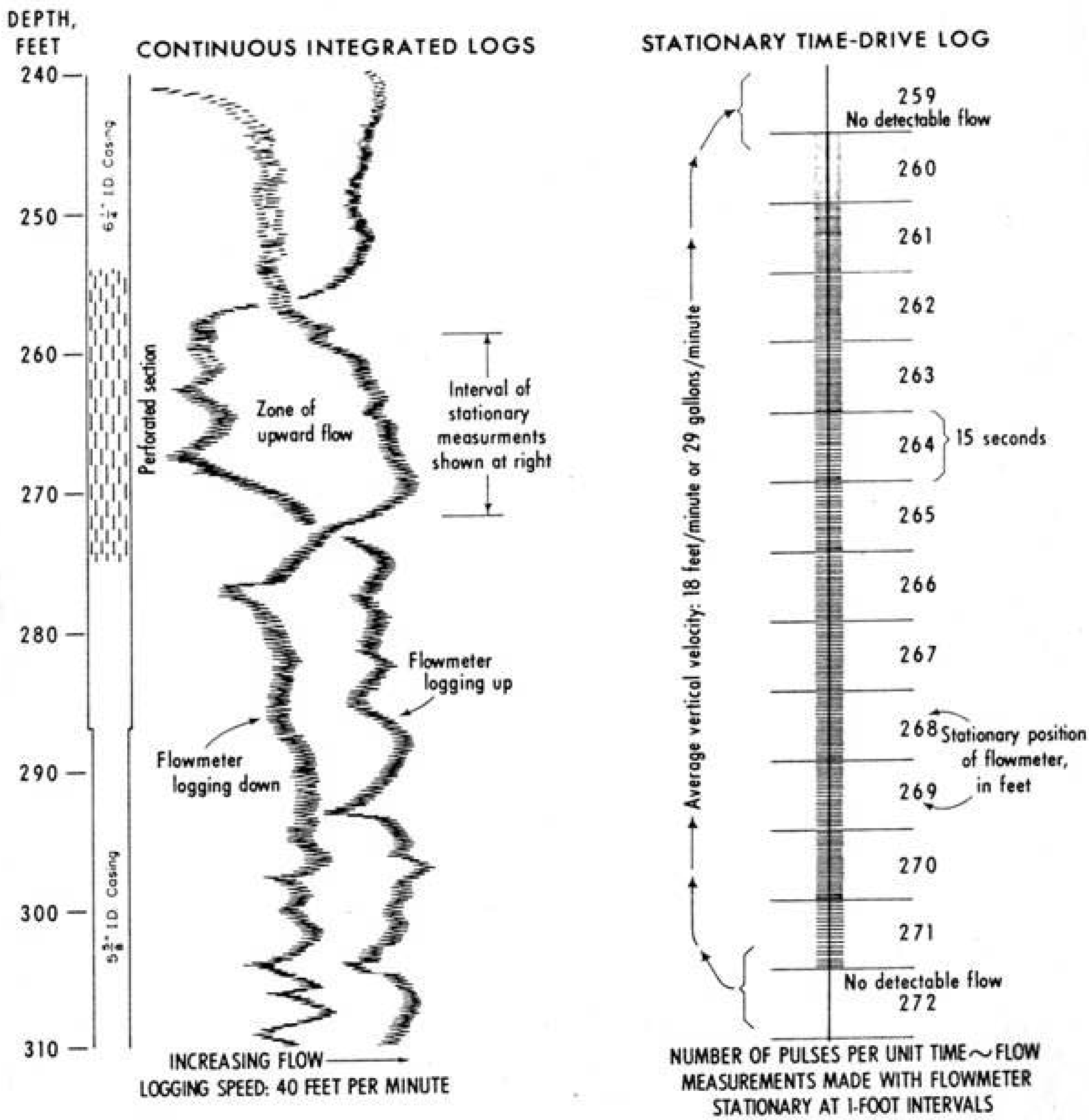


Figure 8.3-4

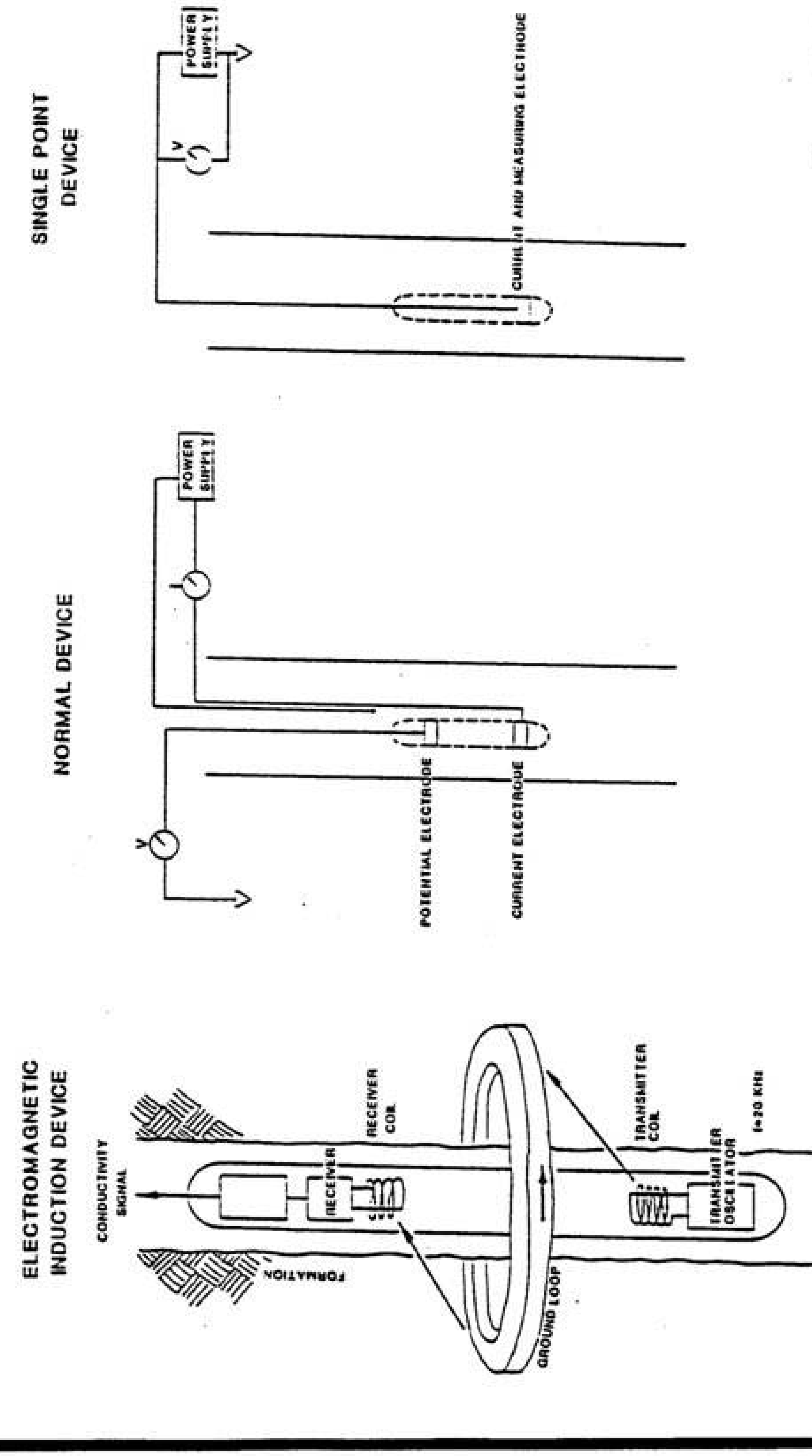
SP Log Example



Source:
Keys and MacCory (1971)

Figure 8.3-5

Example of Flowmeter Log



Source: LABO (1987)

Figure 8.3-6
Resistivity Probes

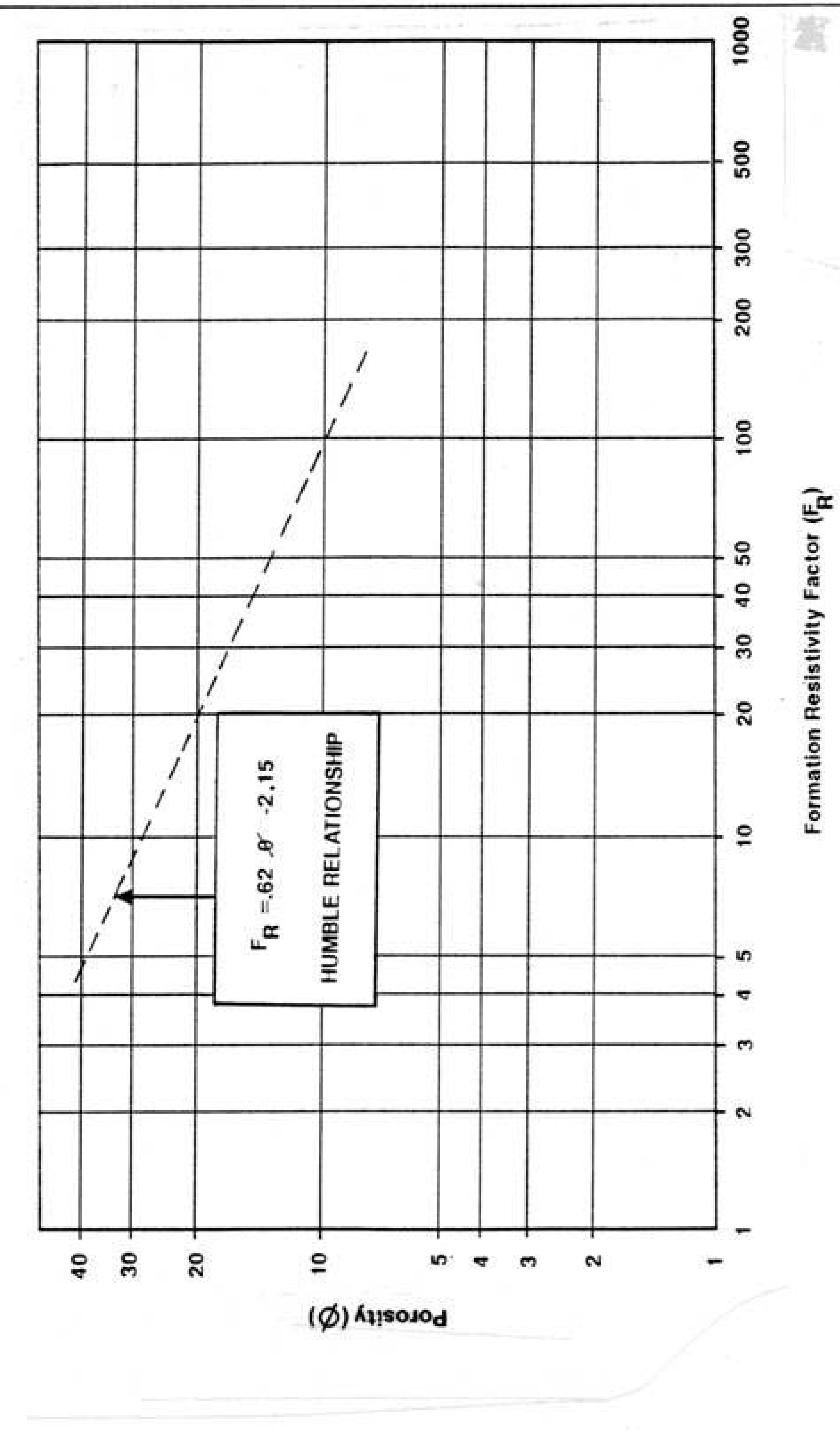
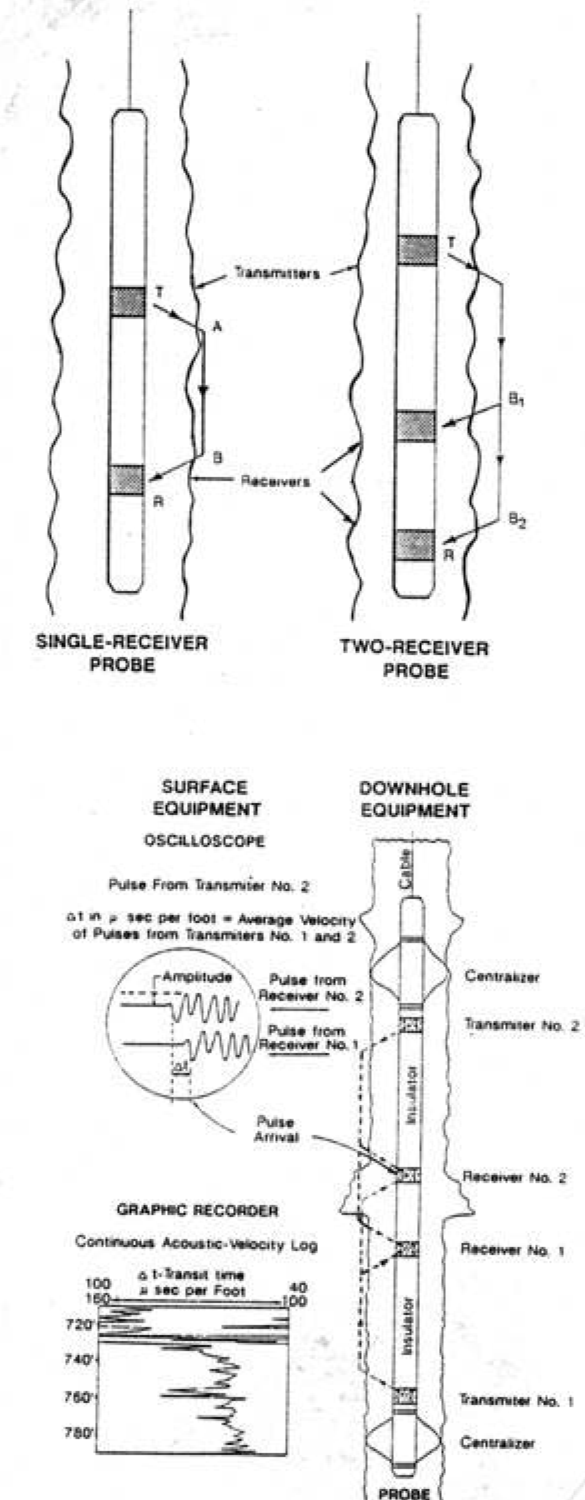


Figure 8.3-7

F Versus o Plot for Sandstones

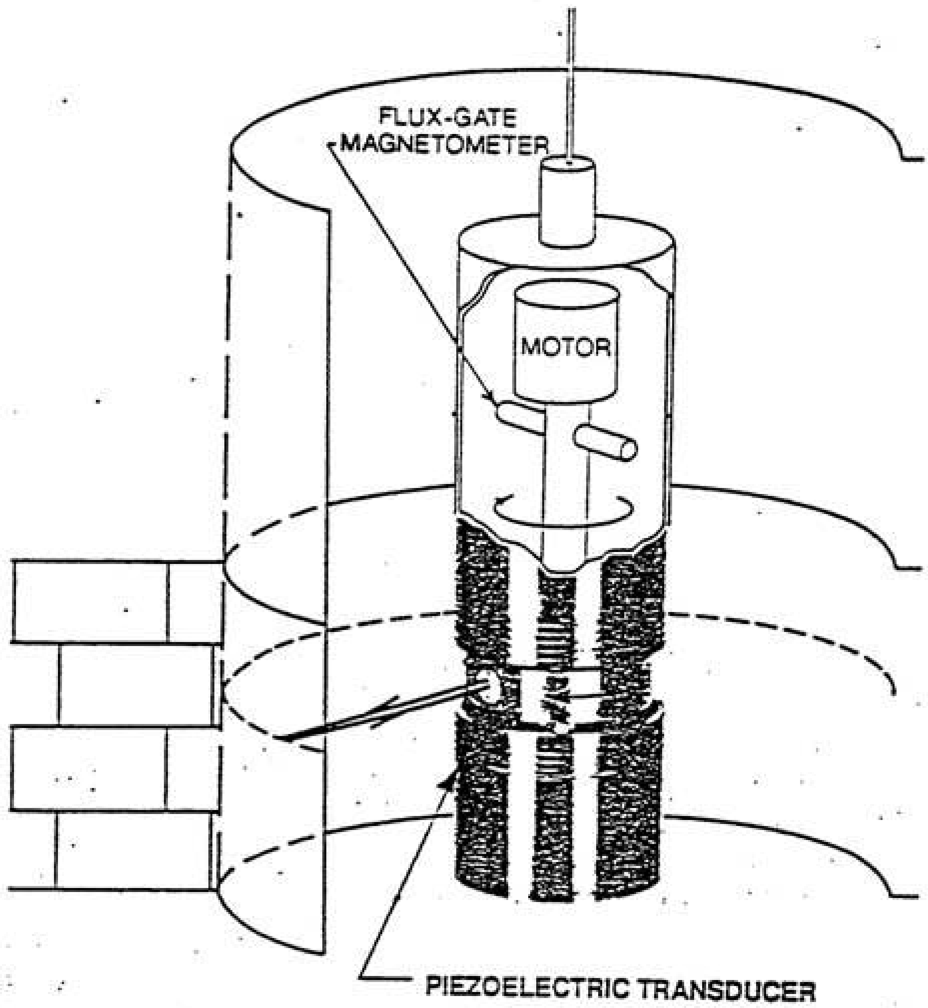
Source: Simplified from Hilchie (1978)



Source:
Keys and MacCary, (1971)

Figure 8.3-8

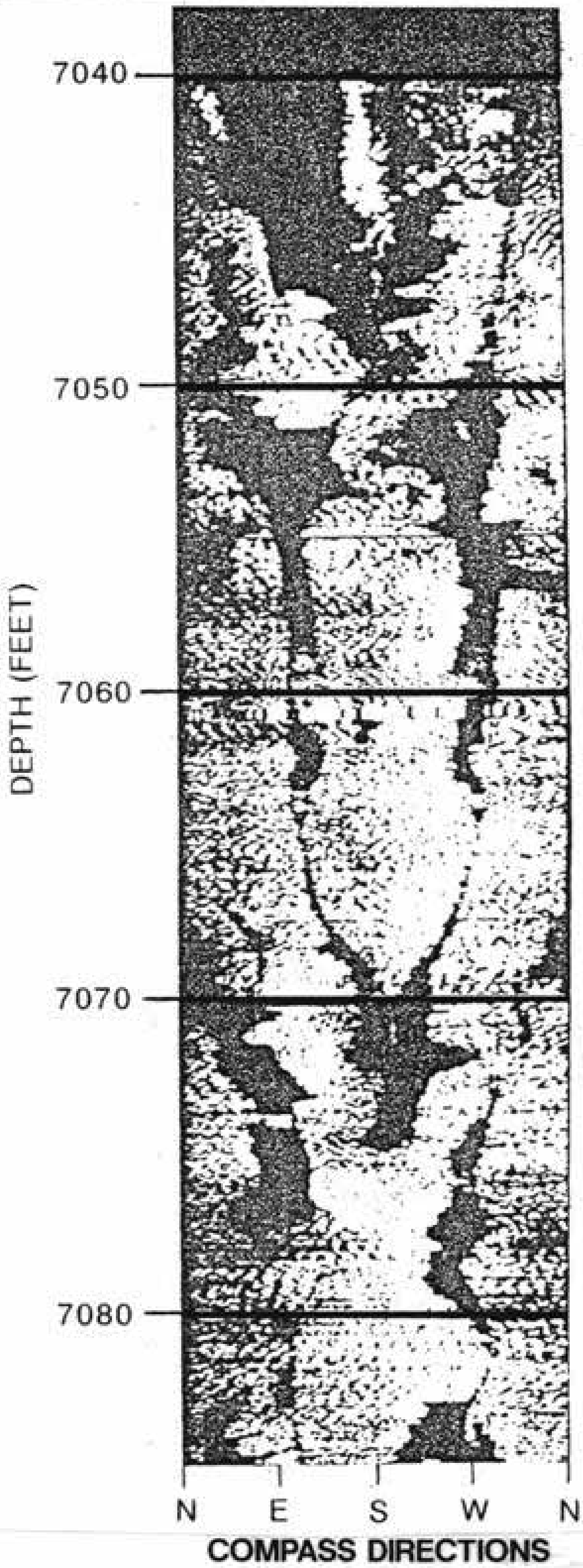
Acoustic Velocity Logging



Source:
Zemanek et al., (1970)

Figure 8.3-9

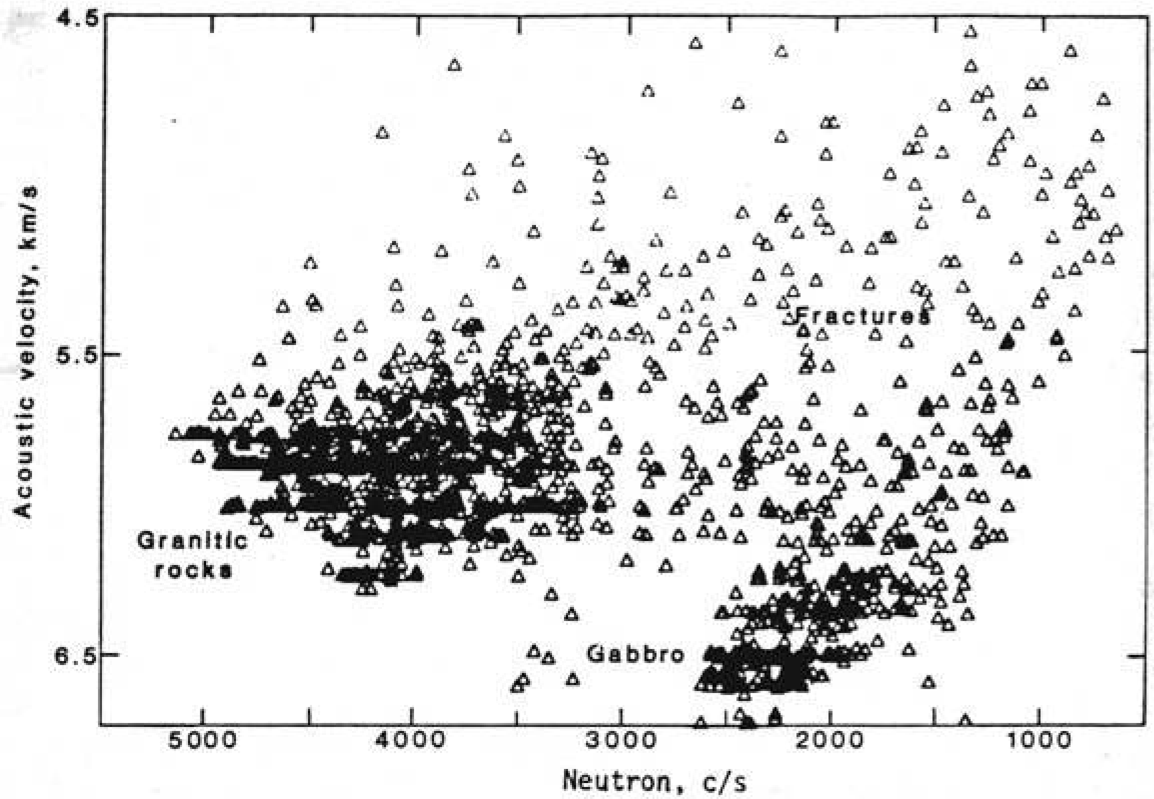
Acoustic Televiewer Diagram



Source:
Zemanek et al., (1970)

Figure 8.3-10

Example of Acoustic Televiewer Image



Source:
Davison et al. , (1982)

Figure 8.3-11

Example of Cross-plot of Acoustic Velocity and Neutron Logs with Geologic Interpretation

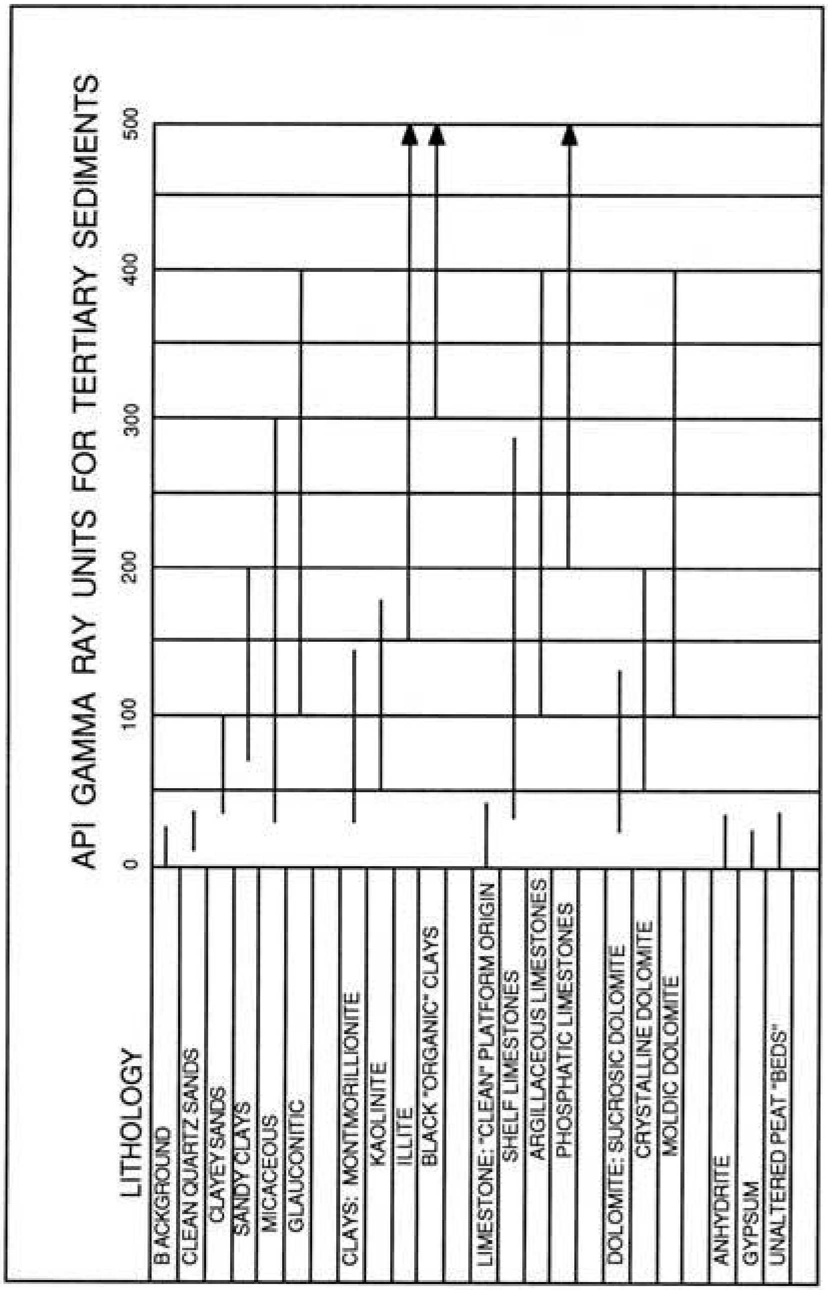
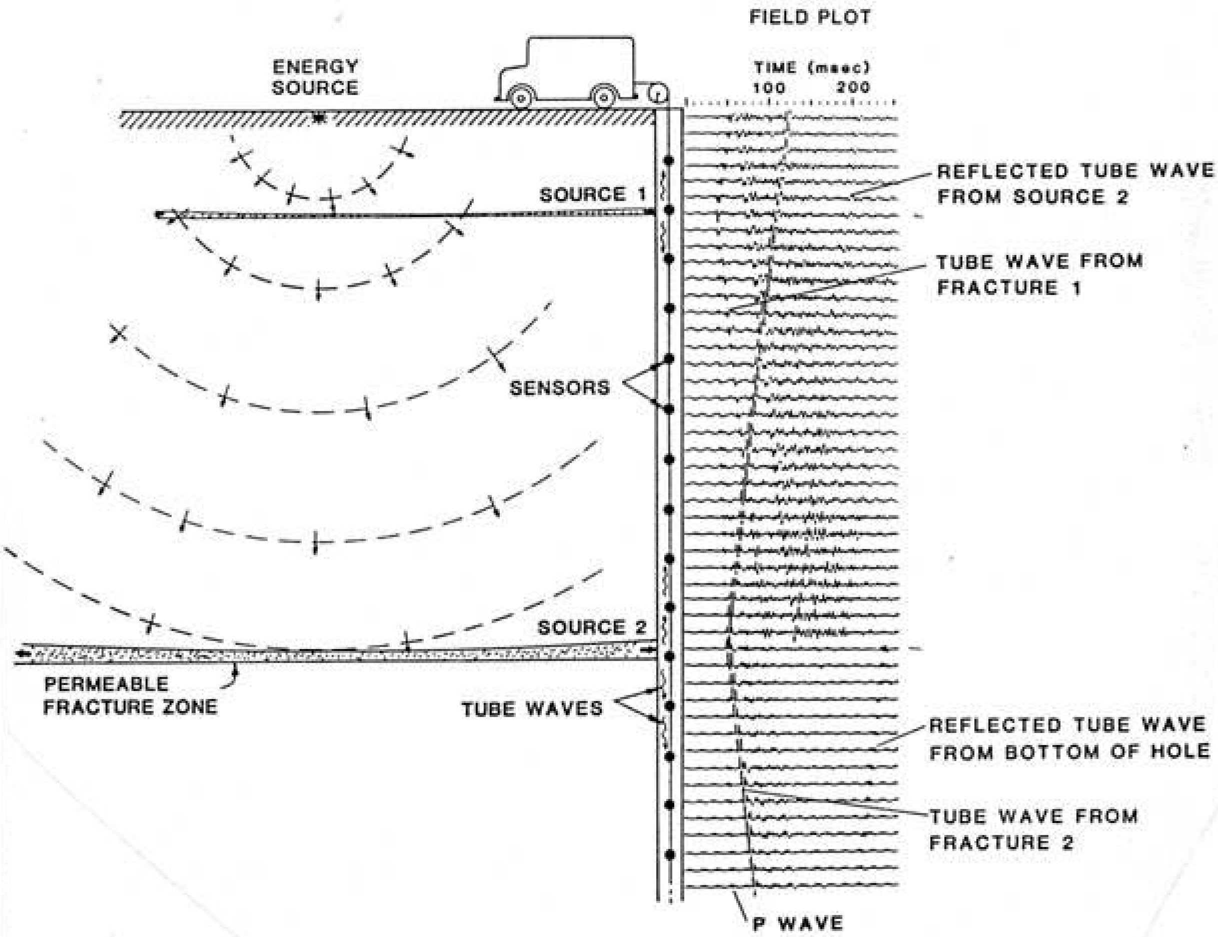


Figure 8.3-12

API Gamma Ray Units for Various Tertiary Sediments

Source:
Kwader, (1982)



Source:
Levine et al., (1985)
Modified by Weston Geophysical (1988)

Figure 8.3-13

Tube Waves Generated by Seismic Energy Incident on Permeable Fracture Zones

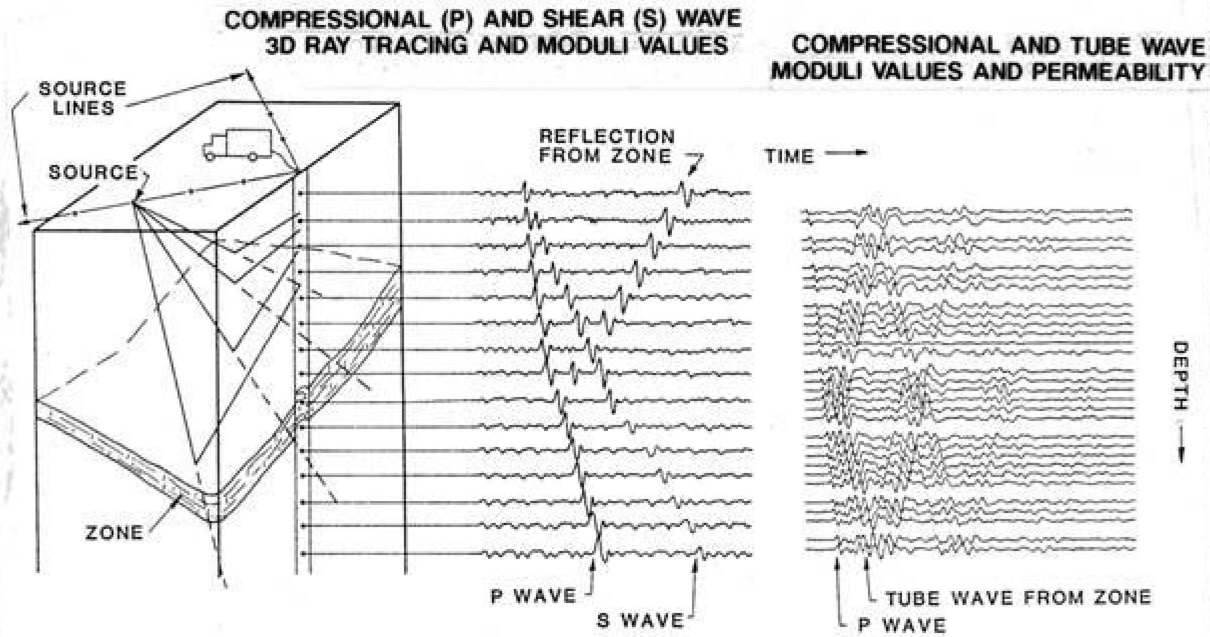
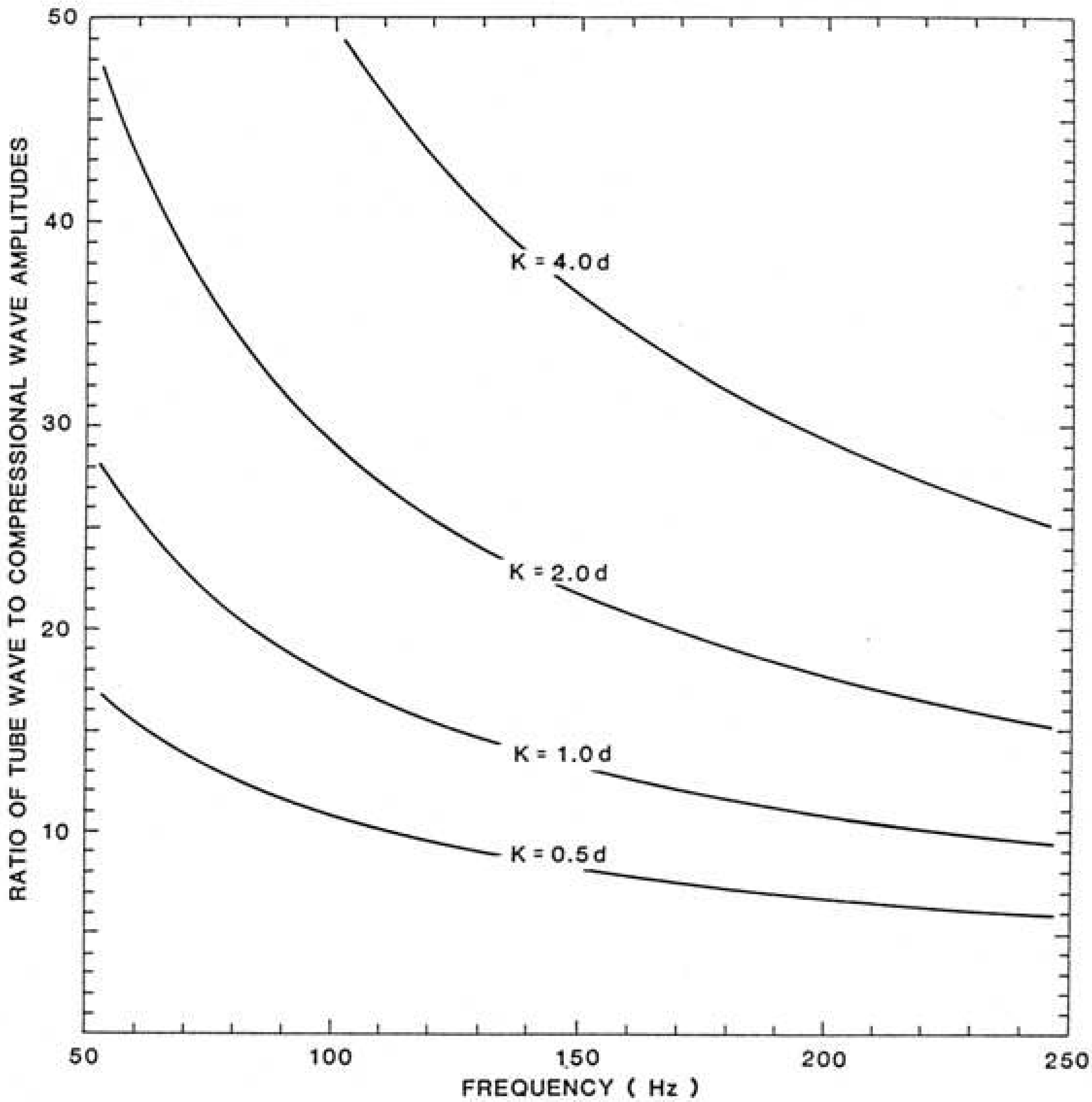


Figure 8.3-14

VSP to Determine 3D Geometry of Strata, Moduli Values and Permeability



Source:
Levine et al., (1985)

Figure 8.3-15

Relationship Between Hydraulic Conductivity and Ratios of Tube Waves to P Wave Amplitudes as a Function of Frequency

SECTION 8.3
BOREHOLE GEOPHYSICS
LIST OF TABLES

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8.3-2	Compressional and Shear Velocities in Rocks	55

GEOPHYSICAL TECHNIQUES

APPLICATION / INFORMATION DESIRED \ MEASUREMENTS-METHOD	Acoustic Amp. and Δ T	Acoustic Waveform	Spontaneous Potential (SP)	Single Point Resistance	Short Normal (16") Res.	Long Normal (64") Res.			Fluid Resistivity		Induction Electromagnetic		Natural Gamma	Focused G-G Density		Neutron-Thermal Neutron	Temperature	Caliper			Flowmeter
Borehole Fluid Quality				●					■								■				
Casing Features	■	■		■					■					△			■	□			■
Cement Features or Bond	■	■												△		△	■	○			
Densities	●	●												△		△		○			
Depositional Environment	●	●	●	●	●	●					*		□	△		△		○			
Fluid Flow			●														■				■
Formation Water Res. (Rw)	●		●			●			■		*		□	△		△		○			
Formation Res. (Rt)						●			●		*							○			
Fracture Detection	●	●			●	●										△	■	○			
Geologic Structure	●	●	●	●	●	●					*		□	△		△		○			
Geotechnical Studies	●	●	●	●	●	●					*		□	△		△		○			
Hazardous Waste Studies	●	●	●	●	●	●			■		*		□	△		△	■	○			■
Lithology - Stratigraphy	●	●	●	●	●	●					*		□	△		△		○			
Mineral Identification	●		●										□	△		△		○			
Permeability Estimates	●	●	●		●	●							□	△		△	■	○			■
Porosity	●	●			●	●							□	△		△		○			
Rock Properties	●	●			●	●							□	△		△		○			
Shaliness Evaluaton	●		●		●	●								△		△		○			
Hydrocarbon Investigation	●	●	●		●	●			●		*		□	△		△		○			
Water Investigations	●		●	●	●	●			●		*		□	△		△	■	○			■
Water Saturation	●	●			●	●			●		*			△		△		○			

○ Open Hole Only

● Open Fluid Filled Hole Only

+ Steel Casing Only

□ No Restriction on Hole

■ Cased or Open Fluid Filled Hole

△ Active Nuclear Log to be Run Only in Stabel or Cased Holes Only

* Open or Non-Steel casing Only - Dry or Fluid Filled

Source:
Adopted from Keys, (1971) and Colog, Inc. (unpublished)

Table 8.3-1

Common Borehole Logging Techniques

Material and Source	Compressional velocity m/s	Compressional velocity ft/s	Shear velocity m/s	Shear velocity ft/s
Granite:				
Barriefield, Ontario	5640	18,600	2870	9470
Quincy, Mass.	5880	19,400	2940	9700
Bear Mt., Tex.	5520	17,200	3040	10,000
Granodiorite, Weston, Mass.	4780	15,800	3100	10,200
Diorite, Salem, Mass.	5780	19,100	3060	10,100
Gabbro, Duluth, Minn.	6450	21,300	3420	11,200
Basalt, Germany	6400	21,100	3200	10,500
Dunite:				
Jackson City, N.C.	7400	24,400	3790	12,500
Twin Sisters, Wash.	8600	28,400	4370	14,400
Sandstone	1400–4300	4620–14,200		
Sandstone conglomerate, Australia	2400	7920		
Limestone:				
Soft	1700–4200	5610–13,900		
Solenhofen, Bavaria	5970	19,700	2880	9500
Argillaceous, Tex.	6030	19,900	3030	10,000
Rundle, Alberta	6060	20,000		
Anhydrite, U.S. Midcontinent, Gulf Coast	4100	13,530		
Clay	1100–2500	3630–8250		
Loose sand	1800	5940	500	1,650

Source: Clark (1966)

Table 8.3-2

Compressional and Shear Velocities in Rocks